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Seismic electric signals (SES) and earthquakes: A review of an updated VAN method and competing hypotheses for SES generation and earthquake triggering

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Abstract
Electromagnetic phenomena are sometimes associated with seismic events, but earthquake prediction using seismic electric signals (SES) has not been seriously considered since the early 1990s. There are several causes: (1) false alarms that have created panics in Greece, and (2) a strong critique of the Varotsos-Alexopoulos-Nomicos (VAN) method used there. An updated VAN method that includes time series analysis has made successful medium-range predictions, and short-range predictions when coupled with seismic time series analysis. Four types of potential mechanisms to create precursory SES relying on deformation effects, temperature effects, ore-mineral movement or groundwater variation are reviewed. Data relevant to each are insufficient to favor a single mechanism. Records of the number of false positive and missed events for an updated VAN method have not been well maintained. False positives appear to be abundant and render the method unusable. Co-seismic groundwater fluctuations are addressed, and two novel hypotheses of earthquake trigger mechanism are also presented: ionospherically induced electric (and resultant magnetic) fields to weaken rock thereby causing failure; and volatiles liberated from minerals additionally promoting rock failure. Recommendations for further study are included.

Keywords
seismic electric signal; earthquake prediction; VAN method; volatile; earthquake trigger.

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1. Introduction

Geophysical research in the 1960s and 1970s included work to examine coupling between earthquake and electrical phenomena, notably from the United States, Soviet Union, China and Japan. Observational evidence shows that compression is associated with a marked decrease in rock resistivity, oriented parallel to the compressive force (Dmowska, 1977). A study in Greece shows the superposition of twenty-four-hour wavelet variations in signals preceding and following an earthquake (Thanassoulas and Tselentis, 1993). See Figure 1. It is not suggested in their study, but such superposition of twenty-four-hour wavelets may be the result of decreased rock resistivity during the seismic event, combined with the typical telluric variation caused by solar flux. For further details on reported seismic electric phenomena going back as far as 1890, see Thanassoulas et al. (2008) and also Karakelian et al. (2000).

The term *seismic electric signal* and the abbreviation SES were coined by a research group in Greece (Varotsos and Alexopoulos 1984a; Varotsos and Alexopoulos 1984b) to describe geoelectrical activity that is measurable and further: (1) it is not associated with a contemporaneous magnetic anomaly, though such an anomaly may follow, or its absence may only be noted in the horizontal component (Varotsos et al., 2003b); (2) it has a rapid rise time; (3) its frequency is 1 Hz or less; and (4) its magnitude is greater than a baseline of background variations in the electrical field (Varotsos et al., 2011b). Magnitudes of 1 to 10 mVm^{-1} have been reported (Thanassoulas and Tselentis, 1993). SES activity may start a week or two before presumed earthquake onset, and also may end a few days before (Thanassoulas et al., 2008). It is not clear that purported SES are distinguishable from artificial signals or from natural background variation, though perhaps this feature is overcome by taking data from more than one observatory for the analysis (Chirkov, 2004; Thanassoulas et al., 2008). Steep fronted electric signals in the Earth can also be caused by ionospheric changes (Chirkov, 2004).

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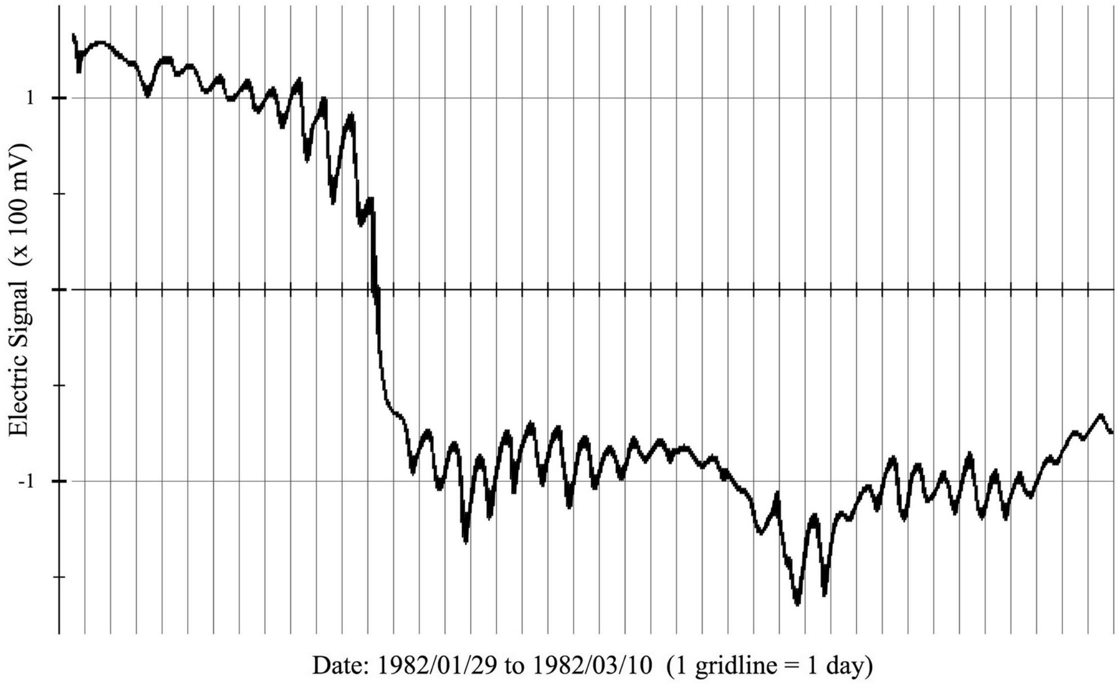

Figure 1. Record of electric field variations before and after the magnitude 4.8 earthquake of February 9, 1982 in the North Aegean. Adapted from Thanassoulas, C., and Tselentis, G., 1993, Periodic variations in the Earth's electric field as earthquake precursors: Results from recent experiments in Greece: Tectonophysics, 224, 103–111, Figure 2.

1.1. Varotsos-Alexopoulos-Nomicos (VAN) Method

In 1981, a network of eighteen electrical stations was set up in Greece, and then connected by telephony in 1983, for earthquake prediction (Varotsos and Alexopoulos 1984a; Varotsos and Alexopoulos 1984b; Varotsos and Alexopoulos, 1987; Varotsos et al., 1988, Varotsos et al., 1993a), with mixed results. The typical VAN method (named for the three co-authors, Varotsos, Alexopoulos and Nomicos) includes choosing a site, laying down sets of short-separation (50 m to 400 m apart) and long-separation (2 to 20 km apart) electrodes in north-south and east-west orientations, along with magnetometers to measure the concurrent changes in the magnetic field (Varotsos et al., 1993a). The multiple electrodes are important in distinguishing noise, and the longer electrodes can demonstrate whether changes in voltage increase with the length

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of the measurement. These length data, combined with polarity data of the pulses, can purportedly distinguish local from regional events.

Finding a location that is relatively insensitive to magnetotelluric variation (i.e. in the directions along which dipole measurements are to be made) is important, since variations in the geomagnetic field can introduce electric field variations that are unrelated to seismic activity (Varotsos et al., 2011b). As a first filter for the electric data, the magnetotelluric data are examined and electric field variations are calculated based on changes to the geomagnetic field. These calculated regional electric field variations are subtracted from the electric field measurements, yielding a baseline from which to look for seismic electric signals (Arvidsson and Kulhánek, 1993; Hadjioannou et al., 1993).

A time lag between the electric and magnetic signals is sometimes measured at the magnetometers. If there is some difference in the rate of transmission of magnetic and electric fields in the rock, then the time lag can also be used to discriminate against local electrical noise: a lag may indicate that the signal has traveled some distance. For some monitoring stations in Greece, comparison with the seismic record indicates that a 1 second time lag is caused by approximately 100 km of travel (Varotsos et al., 2001a; 2003b; 2011b). Note that the absence of an associated magnetic field anomaly may be because a resulting seismo-magnetic field is too weak compared with background noise to detect (Johnston, 1997).

Initially, a measuring station is calibrated: A station’s electric data are compared with seismic data, to see whether seismic events are correlated with anomalies recorded in the electric data, and from which region. This procedure is used to build the selectivity map of the station (Varotsos and Lazaridou, 1991). The selectivity map may show the area where seismic signals produce electrical phenomena detectable at a station, and a geophysical model may be made to validate the selectivity calculated with observed data (Huang and Lin, 2010).

In Greece, major ophiolite suture zones divide the occurrence and character of purported seismic electrical phenomena (Papanikolaou, 1993). See Figure 2. Electric transmission through crystalline rock is affected by chemistry and form, with mafic rock being more suitable than felsic, and dikes purportedly being much better locations for stations than sills. Because of selectivity, a station may be sensitive to seismic activity at a distance (150 to 200 km), but not to local activity. Note that controlled experiments using artificially generated signals have duplicated this feature, selectivity, in the transmission of the electrical energy through the crust (Huang, 2005). The conductivity of the rock

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mass and hypothesized conductive channels are used as a basis for the selectivity modeling.

Figure 2. Observed selectivities of three SES stations, Greece. Ophiolite zones separate the Ioannina and Assiros stations; and the Keratea station is sited on a granitic dike. Adapted from Papanikolaou, D., 1993, The effect of geological anisotropies on the detectability of seismic electric signals: Tectonophysics, 224, 181–187, Figure 1.

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The station is then used to gather predictive data. The location of a signal is deduced from the variance between north-south and east-west trending electrode pairs, correlated with previous seismic detection history. Magnitude is calculated according to the following equation:

$$\log\left(\frac{\Delta V}{L}\right) \approx mM_L + b \qquad (1)$$

where ΔV is the change in electric potential in millivolts, L is the length of the electrode spacing in meters, m is empirical and takes a value from 0.34 to 0.37, M_L is the local magnitude and b is empirical and based on previous data, with values different for NS or EW electrodes, but the slope (0.34 to 0.37) is the same for both (Varotsos et al., 1993a). No vertical (**z**) component of the electric field was recorded in the above studies, nor have correlations been made to rule out atmospheric and weather influences on the fields. Other sources of electrical phenomena, such as man-made interference (e.g. heavy use of electrical lines for a planned construction project), or local electrochemical alterations (e.g. corrosion of the electrodes) are tracked manually. Several measurement sites in the French Alps have been established following this method, with some preliminary selectivity completed (Maron et al., 1993), as has a set of stations in Japan, where telephone cables were used for the electrodes (Kawase et al., 1993). Both show correlative results between seismic activity and electric phenomena.

1.2. Criticism of the VAN Method

Initial criticism of the VAN method focused on a few features of the observed data. Notably, purported SES events typically occur in a period before major seismicity, but not concurrent with it. A candidate mechanism must therefore be able to cause precursory signals but not stronger coseismic signals. This rules out mechanisms that rely on abrupt changes to the local stress field that match the stress drop that occurs with seismicity. Likewise, the magnitudes of the observed electric signals at the surface are high (with fields of about 2 x 10^{-5} V m^{-1}), and events at earthquake-focus depth might need to produce immense signals (10^5 A • m or more) to match observation (Honkura and Kuwata, 1993). Thus mechanisms that occur close to the surface are to be favored (Johnston, 1997; Park et al., 1993; Park, 1996), for example, fluctuations in groudnwater (Varotsos et al., 2019). Critical work was organized in 1993 (Tectonophysics, Volume 224) and 1996 (Lighthill, 1996), and highlights seven features of this VAN method that are problematic:

(1) There is no one-to-one correlation between signals recorded and earthquakes, and perhaps 50% of the larger events are missed (Hamada, 1993). The cut-off magnitude one chooses changes the results of the statistical analysis, and it may be the case that purported SES are organically unrelated to seismic events. Thus the burden of proof is high.

(2) There are two types of temporal correlations recorded: a single signal for a single event, and multiple signals for a period of seismic activity. The second of these yields no definite timing for the prediction (but rather an approximate range, e.g. a few weeks to a few months) (Varotsos et al., 1993a). A new VAN method addresses this challenge by switching to seismic data for the short term prediction protocol following a medium term SES time series analysis.

(3) The transmission of purported seismic electric signals is selective, and a station may only receive seismic signals for a specific region, perhaps not strictly related to distance. The selectivity bias needs to be calibrated with other stations in the network and is subject to human error (Varotsos et al., 1993a). This is a methodological constraint but can be overcome by artificially producing SES *in situ* for additional data if the mechanism causing presumed SES is close to the surface.

(4) Inaccuracy of location, based on selectivity, highlights the unknown origin of supposed SES (Dologlou, 1993a). A candidate mechanism must be able to cause precursory signals that match observation, i.e. occurring during a precursory phase but not during the seismic event itself, and with voltages that are physically observed. This may be partially addressed: (i) by gathering more experimental data to determine or rule out causes of what are taken as SES. Work to determine causes of presumed SES is ongoing (e.g. Dahlgren et al., 2014; Freund, 2007a; 2007b). If a physical mechanism is confirmed, location can be improved (ii) by adding more stations to networks, so that SES can be triangulated more often. The VAN network has lost stations from lack of funding (Varotsos et al., 2011b), despite the extant work by Chirkov (2004) and Thanassoulas et al. (2008), for example, showing good location constraint with two-station monitoring.

(5) Confusion exists between man-made and so called seismic electric signals (Pham et al., 1998). This is still an issue despite attempts to justify revising the results of the Pham et al. paper *post hoc* (Sarlis et al., 1999). Better

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curation of a catalog of artificial electric events near each station may help to mitigate this issue.

(6) Building the selectivity map of a station is prone to a lack of falsifiability, in a region where earthquakes are common enough that correlation is a given (Kagan, 1997). This can potentially be overcome (i) by taking a long time series of data (e.g., years), not just a few weeks before and after the earthquakes; (ii) by using reference stations to cancel out background signals more effectively (Johnston, 1997; Park, 1996); (iii) by artificially producing control SES *in situ*; and (iv) by using more rigorous statistical testing.

(7) Some problems of scientific rigor have been noted, especially regarding conflicts in choosing whose calculated earthquake seismic data to use for correlations (Drakopoulos et al., 1993; Varotsos et al., 1993b). The data from the VAN group are reportedly posted on arXiv, a pre-print archive of scientific papers hosted by Cornell University (Varotsos et al., 2011b). Notwithstanding, the author and others have not been able to locate a list of predictions on arXiv. What is listed in an arXiv search are pre-prints of articles—and not a list of predictions with associated data. In addition, the VAN researchers have been in the habit of counting close predictions as true predictions. Thus, even with the articles that are extant, it is difficult to establish an accounting of the rates of missed events (misses) and of predicted events that didn't occur within the specified parameters (false positives). Data from the VAN researchers are lacking. Scientific rigor continues to be an issue.

The statistical significance of the predictions issued by the VAN team was the subject of a print debate organized by *Geophysical Research Letters* in volume 23, number 11, May 27, 1996, under the title "Debate on VAN." In this debate, Varotsos et al. (1996a) respond to unfair criticisms of some of their earthquake lists (*cf.* Mulargia et al., 1996; Varotsos et al., 1996b). Note that earthquake catalogs are curated, and typically there is leeway in what is included based on professional judgement, e.g. whether aftershocks are included as separate events—and the criticism against the VAN group here is by pointing out that the catalog used is slightly different from a standard one. The debate in the journal is acrimonious and neither side concedes any points. Varotsos et al. (1996c) also reiterate the principles under which their work is operating and invite attempts at replication by scientists who are critical.

To test the statistical significance of SES, one might first determine the criteria for SES signal definition and earthquake event selection. Once the lead time and alarm window are selected, these two parameters should be fixed throughout the test. Note that there is a difference of opinion between Uyeda

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(1996) and Hamada (1993), on the one hand, and Kagan (1997) and Wyss (1996) on the other, relating to statistical significance, in the main because correlations are only very strong with $M_L \geq 5.0$ (or perhaps 5.5) earthquakes, whose occurrence is infrequent enough that the data population is too small for statistical analysis. For example, eight $M_L \geq 5.5$ earthquakes occurred in Greece from January 1, 1984 through September 10, 1995, and the VAN network forecast six of these (Uyeda, 1996)—yet during the period February 1987 to June 1995 they issued predictions for 94 events of $M \geq 5.0$ (Kagan, 1997). The VAN predictions completely spanned the time period with two-month windows. False positives are thus so high as to render the original VAN predictions unusable.

Finally, each of the seven features listed above suggests doubt, yet are less damaging than the manner in which the media, politicians, the VAN team and others involved in SES earthquake prediction in Greece allowed for public misperceptions to cause panic (Papadopoulos, 2014). More than anything else, public panic has created ill will. In short, using presumed SES to predict earthquakes (1) has not always been received with professionalism by the scientific community, (2) has not had unqualified utility in predicting events, and (3) has not been communicated to the public with appropriate care.

For example, one panic is detailed in Lazaridou-Varotsos (2013, p. 157), wherein the VAN team predicted two earthquakes in Athens, in September 1999, and that prediction was given by a third party to the press. A mainshock was shown to be comprised of two events, but the public thought that there was another imminent quake, and this anticipation created a panic. This occurrence is not unique: "On the social level, the VAN and other predictions often caused great concern, panic, and cancellation of thousands of tourist visits e.g., documented in press reports of ... January 1991, regarding the VAN prediction in Thessaloniki" (Papadopoulos, 2014, p. 236). This fits the characteristics of a false alarm (Drakopoulos and Stavrakakis, 1996) despite increased seismicity in the area for the period immediately following the prediction window reported publicly in the press, even though the published academic prediction is more circumspect (Varotsos et al., 1996d). The process in Greece has served to motivate a code of ethics in earthquake prediction (Papadopoulos, 2014).

2. Material and Methods

The research is a review of the available work related to the updated VAN method using time series analysis, and of hypotheses for how presumed SES might form.

3. Results

3.1. Time Series Analysis of Presumed SES

In 2001 Varotsos et al. (2001b) published updated work with SES using time series analysis, and elaborated on this in 2002 (Varotsos et al., 2002). For testing the coherence of the electric signal data, they use a detrended fluctuation analysis (DFA) (Varotsos et al., 2003a; Bashan et al., 2008), breaking the data into time-segments which can be graphed separately with polynomial modeling functions of various orders, generally one (linear), two (quadratic) and three (cubic). A measure of the variation in the data (as expressed by the square root of the sum of the squares of the lengths of data where there are no polynomial trends) is then taken as a power law of the time-segment size chosen:

$$Var(s) \approx s^a \qquad (2)$$

where s is the time-segment size, $Var(s)$ is the variation in the data described above, and a is an indicator variable. If $a \approx 0.5$ then the signal is incoherent and there is no pattern on a range of scales. If $a < 0.5$ then the data are anticorrelated, with scaling indicating some change in the trend according to scale. If $a > 0.5$ then trends in the data are correlated across a range of scales, and therefore coherent. This new method is summarized in Varotsos et al. (2011b).

For SES, DFA leads to $a \approx 1$ for four orders of magnitude in s. For variations in the magnetic field (spikes of alternating sign) which accompany major earthquakes (moment magnitude approximately equal to 6.5 or greater), $a \approx 0.5$ for $s < 12$ seconds (indicating white noise), and $a \approx 0.89$ for $s > 12$ seconds (indicating a coherent trend) (Varotsos et al., 2009; 2011b). White noise is ubiquitous in natural signals, due to the nature of how random distributions occur (Ming Li and Lim, 2006).

For looking at the signals themselves, the updated method introduces two quantities, χ_i and Q_i:

$$\chi_i = \frac{i}{n} \qquad (3)$$

where χ_i is the natural time coefficient, i is an integer based on the order of events (i.e., the i-th event), and n is the total number of events. Q_i is the quantity of energy (electric, seismic or other) released by the process being studied. The product $\chi_i Q_i$ assigns more weight to the most recent and the largest energy events.

A related quantity, p_i, is the fractional quantity of energy, defined by

$$p_i = \frac{Q_i}{Q_{tot}} \quad (4)$$

where p_i is the fractional quantity of energy of the i-th event, Q_i is the energy released by the i-th event, and Q_{tot} is the total energy released during the period of study. This mathematical framework is called natural time analysis by Varotsos et al. (2001b) and can be applied to other systems, such as electrocardiograms (Abe et al., 2005). A few scientists outside the larger VAN group have taken up this technique in relation to various phenomena: observed seismicity (Ramírez-Rojas and Flores-Márquez, 2013), earthquake occurrence trends (Midya and Gole, 2014), earthquake mechanics (Hristopulos and Mouslopoulou, 2013) and observed phenomena in astrophysical objects (Дёмин et al., 2006).

The normalized power spectrum of a set of events in natural time is given by

$$\Pi(\nu) = \left| \sum p_i e^{\boldsymbol{i} \nu \frac{i}{n}} \right|^2 \quad (5)$$

where $\prod(\nu)$ is a modified power spectrum, $\sum$ signifies summation, for $i = 1$ to n, p_i is the fractional quantity of energy for the i-th event, e is the euler number, 2.71828..., $\boldsymbol{i}$ is the square root of negative one, ν is an angle in radians times 2π and is present to model the spectrum in a cyclical framework, i is the event index, and n is the number of events. The quantity ν is plotted versus $\prod(\nu)$ to get an indication of trends in the event energy (Varotsos et al., 2011b). Cyclical variation is an explicit assumption of this formula and of spectral density calculations generally if they include an angular frequency term. Note that a power spectrum is typically expressed as the squared amplitude of the Fourier transform, that is, the Fourier transform times its complex conjugate.

To go on: One variance term used for critical discrimination in natural time is given by

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$$\kappa_1 = [\sum p_i (\frac{i}{n})^2] - [\sum (\frac{i}{n}) p_i]^2 \quad (6)$$

where κ_1 is the variance in natural time, $\sum$ signifies summation, for $i = 1$ to n, p_i is the fractional quantity of energy for the i-th event, i is the event index, and n is the number of events. This variance puts extra weight on p_i.

For a uniform distribution of data, with χ_i and p_i each taking values between 0 and 1, $\kappa_1 \approx 0.0833...$ or 1/12. Empirically, with SES data, if $\kappa_1 \approx 0.070$ the SES are valid and indicate an impending seismic event (Varotsos et al., 2011b). SES datasets with values of κ_1 between 0.070 and 0.083 are indeterminate and those above 0.083 can be considered noise. Typically, a time period of at least three weeks passes between the detection of true SES in a region and the occurrence of the largest associated seismic event (Varotsos et al., 2011b).

Another variance term for exploring criticality in natural time is given by

$$S_n = [\sum [(\frac{i}{n}) \ln (\frac{i}{n}) p_i]] - [[\sum (\frac{i}{n}) p_i] \ln (\sum (\frac{i}{n}) p_i)] \quad (7)$$

where S_n is the entropy in natural time analysis, $\sum$ signifies summation, for $i = 1$ to n, i is the event index, n is the number of events, ln signifies the natural log function, and p_i is the fractional quantity of energy for the i-th event. This variance also puts extra weight on the energy term, p_i. The term S_n, entropy in natural time, is based on numerical signal data and does not indicate a thermodynamic relation. It is related to the field of information entropy (Shannon, 1948).

For a uniform distribution of data, with χ_i and p_i each taking values between 0 and 1, $S_n \approx 0.0966$. Empirically, with SES data, if S_n values (and reversed-order S_n values) are markedly lower than this, the SES are valid and indicate an impending seismic event (Skordas et al., 2019; Varotsos et al., 2008; 2011b).

A third variance term in natural time analysis is calculated by reversing the order of the energy data, and subtracting the value of this new inverted S_n from the original S_n. This is the time-reversal entropy in natural time analysis, ΔS_n. This variance is most sensitive to the ordering of the signal data.

For all these terms in natural time, Q_i can be any energy term, and need not be the magnitude of electric signals. For example, the moment magnitude of seismic events may be subsituted for Q_i, and the evolution of seismic data may be analyzed in natural time. The value of $\kappa_1 \approx 0.070$ indicates that the time series may have reached a critical state, and a large seismic event might be imminent in the region being studied (Sarlis et al., 2008; 2010). The results "outperform chance but are not spectacular if not supplemented with SES detection" (Varotsos et al., 2011b, p. 278) as discussed below.

The current protocol for earthquake prediction is as follows. SES are analyzed for $\kappa_1 \approx 0.070$, indicating criticality. Once a critical state is found, the region for the impending seismic activity is calculated based on the geometry of the SES occurrences. The ratio of the long and short electrode signals of NS and EW orientation are plotted using the sensitivity map for the detection station, which was previously made from correlations between electric signals and seismic signals in the public record, and an estimate of the critical area is made. The predictive magnitude is estimated with Equation 1. Then the SES are set aside. The next focus is to use natural time analysis on the seismic (not electric) signals occurring in the critical region.

The procedure is as follows. The order index i is set to zero, and a new time series is constructed as new seismic data are recorded. The difference is noted between $\prod(v)$ of this seismic data and

$$\Pi(v)_{ideal} \approx 1 - 0.070\, v^2 \qquad (8)$$

where $\prod(v)_{ideal}$ is an ideal power spectrum, v is an angle in radians times 2π. Values of v for $\prod(v)_{ideal}$ are restricted to between 0 and 0.5. If $\prod(v)$ approaches $\prod(v)_{ideal}$ from below for the seismic data, or if $\kappa_1 \approx 0.070$ for the seismic data, then the critical state is indicated, and a major earthquake is imminent, generally occurring within a few days. The location and magnitude of the impending earthquake are taken from the SES data analysis, described above.

For increased accuracy, another updated method (Varotsos et al., 2011b; Varotsos et al., 2017b), which splits all the seismic data into overlapping regions (like a giant Venn diagram of rectangles, where each region includes at least two seismic epicenters), indicates an impending critical seismic state when the distributions of κ_1 values for the regions that include the last seismic event have a maximum at 0.070. Further parametric analysis can be done to distinguish these minima from those which do precede major seismic events, for example, by finding β, the smallest value of the ratio of the standard deviation of κ_1 divided by the mean of κ_1 for a series of κ_1 calculations over a period of time.

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The above methods and parameters described are based on empirical attempts to optimize the data, and have been successful in predicting all but three of the 28 major earthquakes from N36 to N41 latitude and E19 to E27 longitude between 2001 and 2010 (Varotsos et al., 2011b). SES were also recorded for two of the three missed events, but data analyses were insufficiently predictive. New predictions are reportedly uploaded to arXiv. These predictions might be searched for with the following terms: seismic, prediction, Greece—yet search results return a list of pre-print articles instead, for example, Sarlis et al. (2019). Without a comprehensive list of predictions it is not possible to construct a rate of false positives. One is left having to guess—thus one is not able to validate the claim nor judge its utility.

A related study of this order parameter (κ_1) in Japan shows a minimum in κ_1 for all six earthquakes of magnitude greater than 7.6 from January 1, 1984 to March 11, 2011 (Sarlis et al., 2013). Note that Sarlis et al. (2013, Figure 3) list approximately 120 minima in κ_1 calculated for this period, and most are not associated with any major (M>7) seismic event. Further research is ongoing (Varotsos et al., 2014) but this method does not appear to have been changed since its introduction in 2011 (Sarlis et al., 2015, Varotsos et al., 2017a).

If there is severe data corruption in the SES detection protocol, as happens, for example, in regions with electric trains causing ground electrification during a period of time, (e.g. running from 06:00 to 22:00) the corrupted data are discarded. The remaining data are then used for SES analysis (Varotsos et al, 2011a). Even with partial data, this protocol might be successful in predicting earthquakes: notably the Izu Island regional earthquake swarm in Japan in 2000 in an *a posteriori* analysis with four days' notice for $M \geq 6$ (Uyeda et al., 2009; Varotsos et al., 2013; 2011b). Yet, without a clear accounting of missed events and false positives reported, these results do not validate the method.

3.2. Mechanisms Causing SES

The presence of co-seismic electric signals during some earthquake events is well-established (Broding et al., 1963; Matsumoto et al., 1998). During rupture, fractoemission can produce the triboluminescence and radio signals characteristic of short-duration SES that occur near the time of an earthquake (Makarets et al., 2002; Takeuchi and Nagahama, 2002; James et al., 2000; Baragiola et al., 2011; Shibkov et al., 2005). Rock fracture can also cause earthquake lightning and its associated radio signal transmission.

Table 1. Hypotheses: SES Generation Mechanisms

Hypothesis		**Mechanism**
Pressure Effects	Charge vacancy	Crystal lattice vacancies carry electric charge
	Displacement	Ions carry electric charge
	Piezoelectric	Charge generated by constituent piezoelectric minerals
	Piezomagnetic	Field generated by constituent piezomagnetic minerals and then induces a charge
Temperature Effects	Thermoelectric	Temperature liberates charge carriers and lattice vacancies to carry electric charge
Ore-Mineral Motion	Ore-mineral motion	Displacement of crystals in ore creates field via induction with geomagnetic field
Groundwater	Streaming potential	Motion of groundwater due to changes in pore pressure creates charge
	Radon decay	Ionization by radioactive decay of Rn creates charge
	Seismic dynamo	Motion of ions in groundwater during seismic events creates electric fields
	Ionospheric origin	Charges originate in the ionosphere and are transmitted via induction

Note: Data relevant to the first three hypothesis categories can be found in the following sources: Charge-vacancy (Dahlgren et al., 2014; Freund, 2010; Helman, 2013; Scoville et al., 2015; Takeuchi and Nagahama, 2002; Varotsos, 2007; 2008; Varotsos et al., 1998; 2003b; 2011b; Wannamaker et al., 2004), Displacement (Varotsos et al., 1999), Piezoelectric (Johnston, 1997; Park et al., 1993), Piezomagnetic (Johnston, 1997; Park et al., 1993; Stacey, 1964; Zlotnicki and Cornet, 1986); Thermoelectric (Dologlou, 1993b; Enomoto, et al., 1993; Freund, 2010; Junfeng Shen et al., 2010; Xuhui Shen et al., 2011; Zhao Chao et al., 2012), Ore-mineral (Helman, 2013).

There is no unequivocal evidence that purported SES signals are pre-seismic. Table 1 gives a summary of some hypothetical mechanisms to create SES, organized by category. Following Varotsos et al. (2019), only mechanisms related to groundwater motions are discussed further. Moreover, one of these, the seismic-dynamo hypothesis (Honkura et al., 2009), should exhibit co-seismic signals and is thus discarded. Other potential mechanisms in Table 1 require unique modes of charge transmission from earthquake focal depth, or do not readily explain how co-seismic signals are lacking, or both. For a schematic diagram of the three retained mechanisms proposed to generate SES, see Figure 3. Note that the last listed groundwater hypothesis, ionospheric origin, rests on the validity of observations of precursory ionospheric changes which are

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themselves currently the subject of a scientific debate. It is included here with the proviso that it ought not be deemed a valid mechanism unless precursory ionospheric changes can be demonstrated.

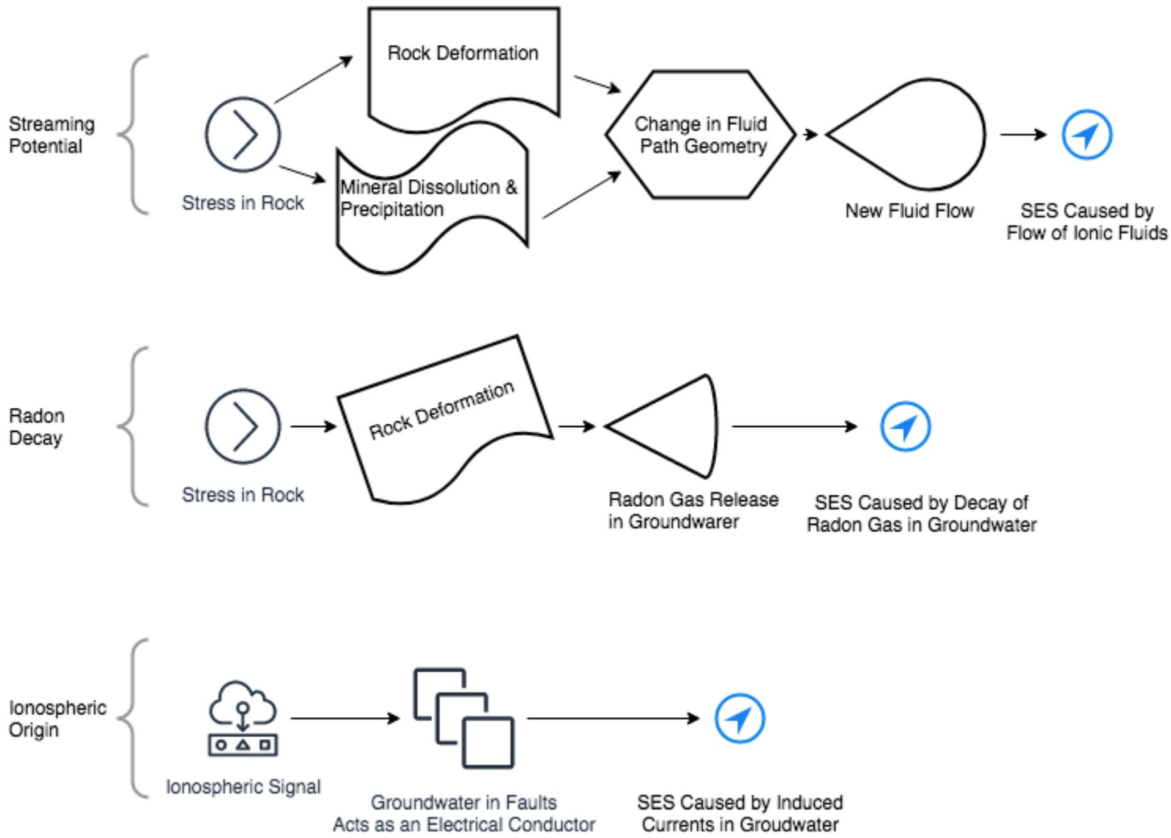

Figure 3. Three possible mechanisms for groundwater causing purported seismic electric signals (SES).

There are three mechanisms by which groundwater movement might generate SES without related co-seismic signals. First, the streaming-potential hypothesis: The location of fluids, notably groundwater, will be affected by changes in pore pressure with changes to both pore position and saturation. These changes can generate electric signals. Second, the radon-decay hypothesis: Rock strain might release radon gas, and this can ionize surrounding material to form ions (Jordan et al., 2011). Third, the ionospheric-origin hypothesis, which is an original contribution of the author contingent on the validation of ionospheric precursors: Electromagnetic coupling between the ionosphere and groundwater may be the source of SES. Ionospheric changes have been reported as precedent to earthquakes (Pulinets et al., 2003). Signals originating in the ionosphere may cause electromagnetic weakening of rock and contribute to failure processes; artificial electrical signals are known to influence seismic dynamics (Chelidze and Matcharashvili, 2003). Water flowing within faults carries dissolved material such as rock flour and ions, and is thus sensitive to changes in the geomagnetic field as are produced by ionospheric changes. Note that this is counter to the prevailing set of hypotheses which focus on terrestrial processes purportedly to influence the ionosphere (Pulinets, 1998).

Table 2. Strengths and Weaknesses: SES Generation Mechanisms

Hypothesis	**Strengths**	**Weaknesses**
Streaming potential	Phenomenon observed in situ	If based on dilatancy diffusion model: (1) strain cracks are too small to account for fluid level changes of 10 to 15 cm; (2) no mechanism for return of groundwater to pre-dlatency levels
	Consistent mechanism for increasing both electric current and electric conductivity	May not account for the rapid rise time of the anomaly
	Phenomenon observed in lab with consistent Hz	May not account for the observed time lag or absence of associated magnetic field anomaly
	Consistent with observed chemical changes during earthquakes	
	Hypothetical source of additional extra water	
Radon decay	Phenomenon observed in situ and in lab	If based on dilatancy diffusion model: (1) strain cracks are too small to account for fluid level changes of 10 to 15 cm; (2) no mechanism for return of groundwater to pre-dlatency levels
	Bursts of radon release perhaps consistent with SES rise time	Not definitive whether rapid rise time is explained
	Radon release consistent with ionospheric anomalies if these exist.	May not account for the observed time lag or absence of associated magnetic field anomaly
Ionospheric origin	Consistent with observations showing no large electric field (100 V/m) surface	Data exist showing near surface increases in ion density pre-earthquake, perhaps implying

Hypothesis	Strengths	Weaknesses
	charging, as would have been needed if SES are inducing ionospheric phenomena	a ground-based mechanism
	Consistent hypothetical source of rock weakening	Data exist showing local increases in light-ion abundance in the ionosphere, perhaps implying an external circuit originating in ground-based phenomena, though a physical mechanism for this remains unclear
	Consistent with transmission as the entire groundwater channel is induced	May not account for the magnitude nor frequency observed in SES
	Consistent with observed ionospheric anomalies on both sides of the Earth–if the validity of an association between ionospheric anomalies and earthquake events is assumed	May not account for the observed SES time lag nor absence of associated magnetic field anomaly

Note: For additional information about the observed SES time lag or absence of magnetic field anomaly, see Section 1.1. Varotsos-Alexopoulos-Nomicos (VAN) Method.

3.3. Data Relating to the Mechanisms of SES Generation

The merits and weaknesses proposed SES mechanisms are given in Table 2 and discussed below.

3.3.1. Streaming-Potential Mechanism

The streaming-potential hypothesis, also referred to as the electrokinetic hypothesis in the literature, was historically favored, along with a mechanism for earthquake formation, the dilatancy-diffusion model (DD), in the 1970s and 1980s, although DD has since fallen out of favor. The DD model describes earthquake nucleation as being caused by strain cracking (dilation), and then fluid motion (diffusion) into the new pore space. The DD model does account for some results, for example, increased radon gas emission (Dutta et al., 2012) and an increase in seismic wave velocity immediately prior to rock failure. It also accounts for the positive correlation between variance in high frequency seismic noise and diurnal ground temperature, as described in Gordeev et al. (1992) since variation in surface heating causes diurnal fluctuations in groundwater pressure.

Some problems exist with DD, notably (Bakhmutov and Groza, 2008), that strain cracks are on the order of microns, and are perhaps too small for water to penetrate; that the variation of underground fluid levels (10 to 15 cm) is too large to be caused by the deformation alone (typically $\varepsilon = 10^{-6}$); and that no mechanism has been found to describe the return of the groundwater to pre-dilatancy levels. The Lazarus (1993) hypothesis, that hydrous to anhydrous transitions in minerals may make up these discrepancies, has not been investigated.

Notwithstanding the above, reports of groundwater changes coincident with earthquakes are numerous (Montgomery and Manga, 2003). Potential mechanisms (besides DD) include consolidation of material, fracturing, large-scale aquifer deformation and clearing material that formerly blocked pores and fractures. In addition, changes to mud content (turbidity) and water chemistry may also accompany seismic activity (Sneed et al., 2003). The water chemistry of interest is dissolved ions. Andrén et al. (2016), for example, report steady decrease in Si and Na ion concentration (ratio 2:1) as well as a much smaller decrease in Ca and an increase in K ion concentrations during the period leading up to two consecutive M > 5 earthquakes in Hafralækur, Iceland. They took well cuttings for petrographic analysis: The groundwater changes are consistent with concomitant replacement of labradorite with analcime and the precipitation of zeolite minerals before and during the seismic activity. Mineral dissolution and precipitation involve ionic transfer and can generate electric signals.

The streaming-potential hypothesis has further literature support in the following: (1) Hautot and Tarits (1998) measured electric potential variations on a ridge separating two lakes in the French Alps, and these lakes underwent water-level variations of several tens of meters on a yearly cycle, enough to induce changes in stress and fluid percolation. Electric-potential variations were linearly related to water-level variations, with an expression of 2 mV per meter of water level change. (2) Hunt et al. (2007) show that electric conductivity and electrokinetic current in a porous water-saturated medium are proportional to the square of the difference between the porosity of the medium and the porosity required for percolation, and also to the square of the difference between the moisture content of the medium and the moisture content required for percolation. Hence, an increase in porosity or moisture content can markedly increase both electrical conductivity and electrokinetic current. (3) Jouniaux and Pozzi (1995) demonstrate that observed 0.1 Hz and 0.5 Hz co-seismic electric signals may be attributed to generation by streaming potentials, based on laboratory experiments with saturated sediments. (4) Lazarus (1993) describes the hypothesis that a pressure-induced transition from hydrous to anhydrous mineralogy may result in the liberation of water contemporaneous with earthquake phenomena. Note that a description of mechanisms to account for the rapid-rise electric signal form seen in SES as well as the observed magnetic-

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field time lag (or its absence) have not been found in the extant literature by the author.

3.3.2. Radon-Decay Mechanism

Observations of radon emission precursory or coincident with seismic phenomena are numerous, but a clear predictive pattern that can be generalized is not seen (Jordan et al., 2011). (1) The radioactivity and short half-life (3.8 days) of radon-222 makes ionization of surrounding atoms a given. (2) Additionally, Roeloffs (1999) and Trique et al. (1999) describe bursts of radon gas caused in an area behind a dam, as increased water creates loading strain on the rock. (3) Likewise, Mollo et al. (2011) demonstrate with laboratory experiments that material failure (fracture surfaces) in rock allows for greatly increased radon emission with strain compared to intact rock. (4) Additionally, Rapoport et al. (2004) successfully model ionospheric disturbances when surface increases to humidity and radon emission give a surface field magnitude of 1.5 kV m^{-1}—a high value that suggests the coupling may not occur. Note that ionospheric anomalies are not necessarily associated with earthquake phenomena. Studies attributing association between ionospheric anomaly and earthquake events (e.g. Pulinets 1998; Pulinets et al., 2003; Pulinets and Boyarchuk, 2004) rely on very limited datasets, and more recent work (Thomas et al., 2017) calls this into question. See the section below, on the ionospheric-origin hypothesis, for an extended discussion.

There are also other unknowns for a radon-decay hypothesis. A mechanism to account for the apparent lag between electric and magnetic field anomalies associated with SES is not clear, though perhaps may be explained by current paths within the fault itself. Further, it is not clear whether sudden releases of radon, and subsequent decay and ionization, could produce the rapid-rise electric signal form of SES.

3.3.3. Ionospheric-Origin Mechanism

This mechanism presumes that there are precursory ionospheric anomalies associated with significant earthquakes. Careful work by Thomas et al. (2017) shows that observed precursory total electron counts (TEC) in the ionosphere for large earthquakes (e.g. $M = 7.0$) occurs infrequently (~20% of events) and this falls within the standard error that results from the small sample size for these events. The total dataset is large ($M \geq 6.0$; $N = 1279$) and shows no evidence of precursory ionospheric events correlated with seismic events, thus calling into question earlier reports where the statistical analysis is smaller or less rigorous.

The Thomas et al. (2017) study does not preclude anticipatory events in the few hours leading up to rupture (Popov et al., 2004) as these are beyond the resolution of the TEC data, nor does it preclude co-seismic or posterior events. These are observed.

Research is ongoing. A dataset of similar size ($M \geq 6.0$; $N = 1339$) filtered into day and night ionospheric TEC also present no statistical significance for precursors, though night signals are stronger than day (Zhu et al., 2018). Yet Ulukavak et al. (2020) show precursory ionospheric TEC anomalies for about 45% of $M \geq 6.0$ earthquakes ($N = 2942$) with a 15-day sliding average across 19-day windows—the 15 days prior to and 4 days after. The posterior correlation weights their analysis.

Some of these analyses, including Thomas et al. (2017), remove TEC anomalies when correlated with natural events such as geomagnetic or solar activity. If ionospheric disturbances are instead part of a mechanism of earthquake rupture via surface induction that weakens the fault, then such removal is not warranted. The ionospheric-origin mechanism is included here with the proviso that it ought not be deemed a valid mechanism unless precursory ionospheric changes can be demonstrated.

The ionospheric-origin hypothesis—proposing that ionospheric disturbances are inducing field changes at the Earth's surface and shallow crust—has support in the following three points:

First, Sorokin et al. (2005) describe how terrestrial surface charging of ~100 V m^{-1} is necessary to cause observed ionospheric anomalies of up to 10 mV m^{-1} purportedly associated with pre-seismic phenomena. This precursory terrestrial surface charging is not observed. To explain this absence, the authors assume the validity of the ionospheric precursors, and model an external electric field caused by aerosols that rise from the ground to account for ionospheric charging. If the ionosphere, instead, is the origin of these signals via solar or other natural processes, then there is no need to explain the lack of near-surface high-voltage electrical charging that ought to occur days before the event. Instead, ionospheric anomalies may be implicated in seismic events.

Second, induced electric and magnetic fields can speed mineral dissolution, precipitation and deformation processes. For example, Conrad (2000) describes decreased flow stress, cavitation and grain growth during granular flow in metals and oxides with an applied electric field. Decreased flow stress denotes material weakening. In Helman (2013), six references are given that show applied electric or magnetic fields increase chemical reaction rates in earth materials; ten are given that show electric or magnetic fields increase deformation rates. Mineral dissolution and rock weakening result.

Third, because of groundwater laden with ions from dissolution of fault gouge, faults have high measured conductivities (Wannamaker et al., 2004), as much as 100 to 1000 times that of surrounding rock (Varotsos et al., 2011b). Geomagnetically induced currents are typically on the order of 200 A in metals (Pulkkinen et al., 2008). Although the conductivity of groudwater in faults is less, faults do form a network of conductors that is plausibly subject to induction from the ionosphere. Thus, the electric fields in the shallow crust induced by ionospheric changes, if valid, may be thought of as a possible triggering mechanism for seismic events because of rock weakening.

There are some significant challenges for this hypothesis to overcome: (1) whether associations between earthquake phenomena and ionospheric anomalies are widespread; (2) whether observed magnitudes of ionospheric anomalies can produce the magnitudes of SES that are observed if common minerals (e.g. magnetite) or dissolved ions in groundwater are the presumed induction targets; (3) whether the frequencies of the signals would match observation; and (4) whether a mechanism exists to explain an observed time lag (or absence) of a magnetic field component. Additionally, observations on the ground coincident with presumed precursory ionospheric anomalies show near-surface increases to ion abundance while the F-layer of the ionosphere shows decreases to average ion mass, implying perhaps a material flux from ground to sky (Pulinets et al., 2003), though this implication needs to overcome limitations on physical mechanism. It relies on a large earthquake preparation area as specified in Dobrovolsky et al. (1979):

$$r = 10^{0.43M} \qquad (9)$$

where r is the radius of the earthquake preparation zone in kilometers and M is the earthquake magnitude. For large earthquakes, the physical plausibility of the extent of an earthquake preparation area of this magnitude is not clear.

3.3.4. Mechanisms Acting in Concert

Yoshida et al. (1998) report several seismo-electric mechanisms acting in concert: They demonstrate that a water-saturated sandstone will accept extra water immediately before rupture (i.e. 9 seconds prior in their experiment) and, based on the magnitudes, timing and polarity of the voltage signals, that both

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piezoelectric and electrokinetic effects are present in the observed electric-potential changes.

It is reasonable to assume that several effects may contribute to presumed SES, as summarized in Table 3. (1) Groundwater and other fluids or volatiles are liberated prior to some earthquakes. (2) Seismicity is characterized by numerous small and very small seismic events in a region, and the seismic-dynamo effect is driven thereby. (3) Heat flow may be increased during earthquakes (Jordan et al., 2011), and (4) heat does generate charge carriers in rock. (5) Deformation mechanisms do create charge-vacancies, and liberate ions, thereby reducing electrical resistivity and creating a signal. (6) Piezoelectric effects may be large enough to detect in some rocks. (7) Stress can create magnetic fields in rock that are larger than background noise (Johnston, 1997). (8) Electrical resistivity in rock is reduced by stress and strain.

Table 3. SES Mechanisms Acting in Concert

Feature	Change
Groundwater, fluids and volatiles	Liberated prior to some earthquakes
Seismic dynamo effect	Pervasively caused by small and micro-seismic events
Heat flow	Increased during some earthquakes
Charge carriers	Liberated by heat
Charge-vacancies and ions	Liberated by deformation mechanisms
Piezoelectric effect	Large enough to detect in some rock during seismicity
Piezomagnetic effect	Field produced by stress
Electrical resistivity in rock	Reduced by stress and strain

For SES that occur long before an earthquake, the combination of fluids, deformation, heat and rock chemistry presumably act in concert. Electric fields from whatever source weaken rock. *In situ*, artificial electrical signals can regulate seismic dynamics (Chelidze and Matcharashvili, 2003). If SES are a valid physical phenomenon, understanding them can help to clarify how earthquakes form.

4. Discussion

Earthquake prediction is a pressing human need. The VAN method of earthquake prediction with time-series analysis, in predicting 25 out of 28 major earthquakes within N36 and N41 latitude and E19 to E27 longitude between 2001 and 2010, purportedly has achieved an 89% success rate. Varotsos et al.

(2011b) provide data for this time period on: (1) misses, when there is no prediction and an event occurs; but (2) false predictions, when one has made a prediction but no event occurs, are not comprehensively reported; nor (3) is the data set large enough to draw unqualified conclusions. Moreover, there are no clear calculations of how the rates of misses and false predictions have changed over time since the VAN group's prediction work started in the late 1970s or early 1980s, though data may be found in Varotsos (2005). A meta-analysis of misses and false predictions by the VAN authors that is explicit would be a useful addition to the literature and might serve to refocus the research and criticism of it.

Earlier, the margin of error in location and earthquake magnitude had been, respectively, 100 km and 0.7, while the lead time had been a few days (Varotsos et al., 1993a; Hamada, 1993). These values fell within public safety requirements. However, rigorous, complete and far-reaching analyses of miss rates and false-prediction rates are necessary for policy makers to make decisions based on conformance with public safety requirements.

Likewise with work in Japan (Uyeda and Nagao, 2018). Published studies there show natural geoelectric and geomagnetic anomalies (Hattori et al., 2013a) likely associated with groundwater and seismic motions (Takahashi et al., 2007) but do not use the time series described in the updated VAN method. Some do use a time series method, and likewise record a high number of false positives, e.g. 66 seismic events with 235 anomalies; 31 seismic events with 287 anomalies (Hattori et al., 2013b). Research using the VAN method in Japan does not report the rate of false positives (Sarlis et al., 2015).

In general, earthquake prediction ought to be underlain by statistical analysis that takes into account: (1) long time series of data (e.g., years), not just a few weeks before and after the earthquakes; (2) statistical study showing that precursory signals are unique, reproducible, and significant, including analysis of false positives; and in the case of SES, (3) quantification of the noise from natural (e.g., lightning and solar-terrestrial) and artificial (e.g., power-grid and electric-train) sources.

Table 4 summarizes opportunities for gathering additional information related to purported SES mechanisms and earthquakes. The radon-gas and ionospheric-origin hypotheses notably rely on the validity of the association of ionospheric anomalies with seismic events. Barring this, the focus ought to be on how tectonic groundwater changes occur, and what electric signals are associated with them.

Table 4. Project Ideas for Future Study

Project	**Information Provided**
Establish new SES stations in other regions	Verify process Refine how selectivity map is developed Optimize to reduce false positives
Develop conductivity map of the Earth's surface	Helps to refine SES selectivity maps
Gather SES data in an area with a known applied electric field	Provides a baseline for evaluating the validity of SES data and station selectivity
Develop global groundwater map	Helps to refine electric conductivity maps of the Earth's surface
Test propagation of signals in rock arising from groundwater variation	Provides data for evaluating the streaming-potential hypothesis, the radon-decay hypothesis or the seismic-dynamo hypothesis
Develop global radon data collection and map	Provides data for evaluating the radon-decay hypothesis
Gather data on hydrous to anhydrous mineral transitions	Provides data to develop a model of co-seismic groundwater fluctuation based on hydrous-anhydrous mineral transitions Provides data for evaluating an electromagnetic hypothesis of earthquake triggering
Develop technique to test whether pre-seismic rock deformation creates short paths for increased fluid flow, and co-seismic rock deformation destroys these short paths and increases the volume of pore space	Provides data to develop a model of co-seismic groundwater fluctuation based on changes in fluid path tortuosity and pore space volume
Develop a map of rock and mineral abundance at depth in the crust	Provides data to build a model correlating electrical energy released from rock and mineral deformation with chemical reactions in the rock and electric signals.
Increase the network of ground stations gathering data from the ionosphere	Provides data for evaluating the ionospheric-origin hypothesis

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Gather data on rock failure from applied electric and magnetic fields and applied stress	Provides data for evaluating the ionospheric-origin hypothesis
Gather data on the net electrical effects of deformation mechanisms present in fault zones	Provides data for evaluating the ionospheric-origin hypothesis
Gather data on temperature changes associated with fault zones	Provides data for evaluating the ionospheric-origin hypothesis
Develop a model to provide data on the magnitudes of the electrochemical potentials of chemical reactions that occur during metamorphism	Provides data for evaluating the ionospheric-origin hypothesis

Finally, study of SES suggests that a re-examination of earthquake trigger mechanisms is in order. Earthquakes might be triggered in nature by electricity or magnetism weakening rock, and SES imply this. It is known both that magnetic fields can weaken earth materials (Li Xiangde, 1997; Tian et al., 2009), and that applied electric fields have some effect on seismic events (Chelidze and Matcharashvili, 2003). Further, earthquakes can be triggered by the injection of fluid into wells at high pressure (Raleigh et al., 1976). A mechanism involving electricity, magnetism and volatiles might be responsible for earthquake criticality. A simplified overview is presented in Figure 4 and may be thought of as follows: Directed forces or pressure creates deformation, and this deformation generates electric charge and magnetic field. The deformation and electric charge provide energy to minerals present to liberate water, radon or other ions and volatiles from within a source rock. The presence of these volatiles generates additional electric charge via groundwater or material motion. The resulting magnetic fields weaken the rock, making it more susceptible to deformation. The additional pressure from volatiles and fluid in the rock pore space weakens the rock further. The release of material also weakens the constituent minerals in the rock. The rock again deforms and generates electric charge and electromagnetic fields, and again liberates water and other volatiles. There are eight positive feedback mechanisms at work. These are listed in Table 5. The process repeats itself until rock strength is overcome and an earthquake occurs. Note that the role of heat is complex in mineral dissolution and material strength and forms additional feedbacks with

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this system depending on the minerals and volatiles present—but in general facilitates chemical and material changes further weakening rock, e.g. by providing energy for chemical reactions and increased plasticity.

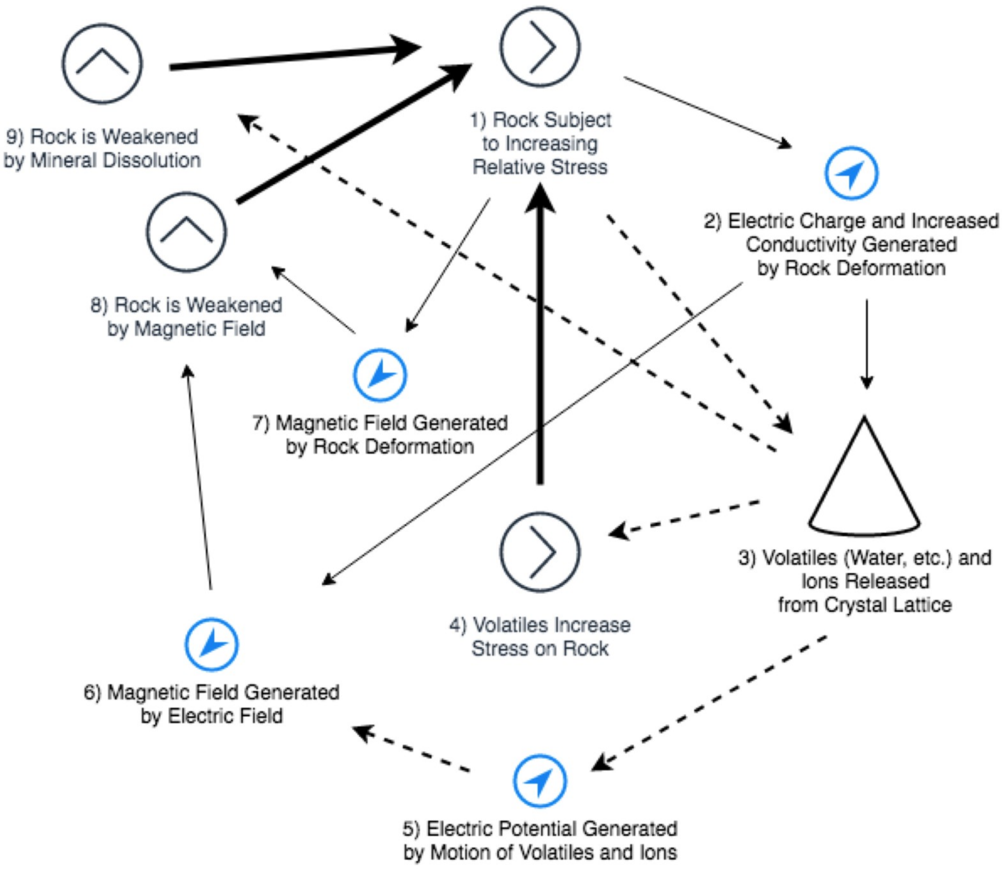

Figure 4. Schematic diagram of a proposed electromagnetic trigger mechanism for earthquakes that comprises eight positive feedback loops. The pathways involving volatiles and mineral dissolution are dashed. Note that heat's effects on the system are not shown.

Testing this feedback hypothesis may require a more intimate knowledge of the process whereby volatiles are liberated from minerals. For example, a significant number of centrosymmetric minerals that exhibit piezoelectricity do so because of the locations of volatiles such as CO_2 or H_2O in their crystal lattices (Helman, 2016). How applied electricity or magnetism can influence crystal lattices to release volatiles from minerals, and whether this release can weaken rock sufficiently to support an electromagnetic earthquake trigger hypothesis are open questions, as are quantifying the influence of electricity and magnetism on the tortuosity of fluid paths in rock. These depend on data that have not yet been gathered.

Table 5. Positive Feedback Loops in an Electromagnetic Trigger Mechanism. Numbers are from Figure 4.

Feeback Loop	Processes
12681	Increased stress - Increased electric charge and conductivity from material change - Magnetic field - Rock weakened - Increased relative stress
12391	Increased stress - Increased electric charge and conductivity from material change - Volatile release - Rock weakened - Increased relative stress
12341	Increased stress - Increased electric charge and conductivity from material change - Volatile release - Volatile pressure - Increased stress
1235681	Increased stress - Increased electric charge and conductivity from material change - Volatile release - Streaming potential - Magnetic field - Rock weakened - Increased relative stress
1391	Increased stress - Volatile release - Rock weakened - Increased relative stress
1341	Increased stress - Volatile release - Volatile pressure - Increased stress
135681	Increased stress - Volatile release - Streaming potential - Magnetic field - Rock weakened - Increased relative stress
1781	Increased stress - Magnetic field from material change - Rock weakened - Increased relative stress

The body of analytical techniques described by Varotsos et al. (2011b) may not be as rigorous as is required, but SES themselves may be a trigger to seismic rupture. The time delay between regional SES and large seismic events might hypothetically be attributed to an interplay of electricity, magnetism and volatiles in rock weakening as hydrological and mineralogical changes occur. A Heckmann diagram, which shows the interplay of various electronic effects on materials undergoing mechanical strain and thermal change, would be useful for this type of modeling (Ballato, 1995).

5. Conclusions

The main question that interests the reader is "Does the VAN method work?" This may be seen as encompassing three questions: (1) whether predictions are predictive; (2) whether predictions issued using this method are actionable; and (3) whether other groups using this method are successful. The answers, unfortunately, are: (1) it is not clear whether they are predictive. The VAN group has done poorly in hosting their data publicly. Raw datasets and a list of predictions including misses and false positives are not present publicly. The updated time-series method describes medium-range predictions that then trigger short-term prediction algorithms using local seismic data, and in principle, this seems a plausible approach to prediction, i.e. via overlap of methods. Mechanisms for SES generation are physical and testable. The updated VAN method remains an unvalidated hypothesis. (2) Predictions issued using this method are not actionable beyond increased local seismic monitoring and increased awareness of earthquake safety. Predictions ought not be assumed correct—with the caveat that increased local seismic activity may be taken as precursory but outside the framework of a validated scientific process. Thus it is up to the relevant governmental body to make decisions in the absence of scientific confidence. Unfortunately the data are not present to make any stronger recommendation. (3) It is not clear whether the high rate of false positives has been overcome in trials in Japan or elsewhere.

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References

Abe, S., Sarlis, N.V., Skordas, E.S., Tanaka, H.K., Varotsos, P.A., 2005. Origin of the usefulness of the natural-time representation of complex time series. Physical Review Letters, 94, 170601. doi: 10.1103/PhysRevLett.94.170601

Andrén, M., Stockmann, G., Skelton, A., Sturkell, E., Mörth, C.M., Guðrúnardóttir, H.R., Simone Keller, N., Odling, N., Dahrén, B, Broman, C., Balic-Zunic, T., Hjartarson, H., Siegmund, H., Freund, F., Kockum, I., 2016. Coupling between mineral reactions, chemical changes in groundwater, and earthquakes in Iceland. Journal of Geophysical Research: Solid Earth, 121(4), 2315–2337. doi:10.1002/2015JB012614

Arvidsson, R., Kulhánek, O., 1993. Enhancement of seismic electric signals using magnetotellurics. Tectonophysics, 224, 131–139. doi: 10.1016/0040-1951(93)90064-Q

Bakhmutov, V.G., Groza, A.A., 2008. The dilatancy-diffusion model: New prospects *in* Proceedings, International Conference: Problems of Geocosmos, 7th , St. Petersburg, Russia, May 26–30, 7, 406–411. Retrieved from http://geo.niif.spb.su/materials_of_a_conference_2008/S/Binder5.pdf

Ballato, A., 1995. Piezoelectricity: Old effect, new thrusts. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 42, 916–926. doi: 10.1109/58.464826

Baragiola, R., Dukes, C.A., Hedges, D., 2011. Ozone generation by rock fracture: Earthquake early warning? Applied Physics Letters, 99, 204101, doi: 10.1063/1.3660763.

Bashan, A., Bartsch, R., Kantelhardt, J.W., Havlin, S., 2008. Comparison of detrending methods for fluctuation analysis. Physica A: Statistical Mechanics and its Applications, 387, 5080–5090. doi: 10.1016/j.physa.2008.04.023

Broding, R.A., Buchanan, S.D., Hearn, D.P., 1963. Field experiments on the electroseismic effect. IEEE Transactions on Geoscience Electronics, 1, 23–31. doi: 10.1109/TGE.1963.271176

Chelidze, T., Matcharashvili, T., 2003. Electromagnetic control of earthquake dynamics? Computers & Geosciences, 29, 587–593. doi: 10.1016/S0098-3004(03)00040-2

Chirkov, Y.B., 2004. The study of local sources of ULF geoelectric signals with steep fronts. Annals of Geophysics, 47, 213–227. doi: 10.4401/ag-3273

Conrad, H., 2000. Electroplasticity in metals and ceramics. Materials Science and Engineering A: Structural Materials: Properties, Microstructures and Processing, 287, 276–287. doi: 10.1016/S0921-5093(00)00786-3

Dahlgren, R.P., Johnston, M.J., Vanderbilt, V.C., Nakaba, R.N., 2014. Comparison of the stress−stimulated current of dry and fluid−saturated gabbro samples. Bulletin of the Seismological Society of America, 104, 2662–2672. doi: 10.1785/0120140144

Дёмин, С.А., Юльметьев, Р.М., Панищев, О.Ю., Замалеева Н.Т., 2006. Приложение нового метода анализа неравноинтервальных временных серий к исследованию рентгеновского излучения астрофизических объектов [Applications of new methods of analysis of time series bumpy intervals to research of x-ray astrophysical objects]: Филология и Культура [Philology and Culture], 7. Retrieved from http://cyberleninka.ru/article/n/prilozhenie-novogo-metoda-analiza-neravnointervalnyh-vremennyh-seriy-k-issledovaniyu-rentgenovskogo-izlucheniya-astrofizicheskih#ixzz3S8NMp0ve

Dmowska, R., 1977. Electromechanical phenomena associated with earthquakes. Geophysical Surveys, 3, 157–174. doi: 10.1007/BF01449191

Dobrovolsky, I. P., Zubkov, S. I., Miachkin, V. I., 1979. Estimation of the size of earthquake preparation zones. Pure and Applied Geophysics, 117(5), 1025-1044. doi: 10.1007/BF00876083

Dologlou, E., 1993a. A three year continuous sample of officially documented predictions issued in Greece using the VAN method: 1987–1989. Tectonophysics, 224, 189–202. doi: 10.1016/0040-1951(93)90072-R

Dologlou, E., 1993b. Thermally stimulated currents in rocks. II. Tectonophysics, 224, 175–180. doi: 10.1016/0040-1951(93)90070-Z

Drakopoulos, J., Stavrakakis, G.N., Latoussakis, J., 1993. Evaluation and interpretation of thirteen official VAN-telegrams for the period September 10, 1986 to April 28, 1988. Tectonophysics, 224, 223–236. doi: 10.1016/0040-1951(93)90075-U

Drakopoulos, J., & Stavrakakis, G.N., 1996. A false alarm based on electrical activity recorded at a VAN−Station in northern Greece in December 1990. Geophysical Research Letters, 23, 1355-1358. doi: 10.1029/95GL03547

Dutta, P.K., Naskar, M.K., Mishra, O.P., 2012. Test of strain behavior model with radon anomaly in seismogenic area: A Bayesian melding approach. International Journal of Geosciences, 3, 126–132. doi: 10.4236/ijg.2012.31015

Enomoto, Y., Akai, M., Hashimoto, H., Mori, S., Asabe, Y., 1993. Exoelectron emission: Possible relation to seismic geo-electromagnetic activities as a microscopic aspect in geotribology. Wear, 168, 135–142. doi: 10.1016/0043-1648(93)90209-5

Freund, F.T., 2007a. Pre-earthquake signals? Part I: Deviatoric stresses turn rocks into a source of electric currents. Natural Hazards and Earth System Science, 7, 535–541. Retrieved from www.nat-hazards-earth-syst-sci.net/7/535/2007/

Freund, F.T., 2007b. Pre-earthquake signals? Part II: Flow of battery currents in the crust. Natural Hazards and Earth System Science, 7, 543–548. Retrieved from http://www.nat-hazards-earth-syst-sci.net/7/543/2007/nhess-7-543-2007.html

Freund, F., 2010. Toward a unified solid state theory for pre-earthquake signals. Acta Geophysica, 58(5), 719-766. doi: 10.2478/s11600-009-0066-x

Gordeev, E.I., Saltykov, V.A., Sinitsin, V.I., Chebrov, V.N., 1992. Relationship between heating of the ground surface and high-frequency seismic noise. Physics of the Earth and Planetary Interiors, 71, 1–5. doi: 10.1016/0031-9201(92)90023-O

Hadjioannou, D., Vallianatos, F., Eftaxias, K., Hadjicontis V., Nomikos, K., 1993. Subtraction of the telluric inductive component from VAN measurements. Tectonophysics, 224, 113–124. doi: 10.1016/0040-1951(93)90062-O

Hamada, K., 1993. Statistical evaluation of the SES predictions issued in Greece: alarm and success rates. Tectonophysics, 224, 203–210. doi: 10.1016/0040-1951(93)90073-S

Hattori, K., Han, P., Huang, Q., 2013a. Global variation of ULF geomagnetic fields and detection of anomalous changes at a certain observatory using reference data, Electrical Engineering in Japan, 182, 9–18. doi:10.1002/eej.22299

Hattori K, Han P, Yoshino C, Febriani F, Yamaguchi H, Chen C-H. 2013b. Investigation of ULF Seismo-Magnetic Phenomena in Kanto, Japan during 2000-2010: Case Studies and Statistical Studies. Surveys in Geophysics, 34: 293-316, doi:10.1007/s10712-012-9215-x

Hautot, S., Tarits, P., 1998. Electric potential variations associated with yearly lake level variations. Geophysical Research Letters, 25, 1955–1958. doi: 10.1029/98GL01139

Helman, D.S., 2013. Metamorphic contributions to electrical phenomena in the Earth's crust, California State University Long Beach [Master's Thesis]. 527 p.

Helman, D.S., 2016. Symmetry-based electricity in minerals and rocks: A review with examples of centrosymmetric minerals that exhibit pyro- and piezoelectricity. Periodico di Mineralogia, 85, 201–248. doi: 10.2451/2016PM590

Honkura, Y. and Kuwata, Y., 1993. Estimation of electric fields in the conducting earth's crust for oscillating electric current dipole sources and implications for anomalous electric fields associated with earthquakes. Tectonophysics. 224, 257–264. doi:10.1016/0040-1951(93)90078-X

Honkura, Y., Ogawa, Y., Matsushima, M., Nagaoka, S., Ujihara, N., Yamawaki, T., 2009. A model for observed circular polarized electric fields coincident with the passage of large seismic waves. Journal of Geophysical Research: Solid Earth, 114, B10103, doi: 10.1029/2008JB006117.

Hristopulos, D.T., Mouslopoulou, V., 2013. Strength statistics and the distribution of earthquake interevent times. Physica A: Statistical Mechanics and its Applications, 392, 485–496. doi: 10.1016/j.physa.2012.09.011

Huang, Q., 2005. Controlled analogue experiments on propagation of seismic electromagnetic signals. Chinese Science Bulletin, 50, 1957–1961. doi: 10.1360/982004-312

Huang, Q., Lin, Y., 2010. Selectivity of seismic electric signal (SES) of the 2000 Izu earthquake swarm: a 3D FEM numerical simulation model. Proceedings of the Japan Academy Series B 86, 257-264. doi:10.3969/j.issn.0001-5733.2010.03.007

Hunt, A., Gershenzon, N., Bambakidis, G., 2007. Pre-seismic electromagnetic phenomena in the framework of percolation and fractal theories. Tectonophysics, 431, 23–32. doi: 10.1016/j.tecto.2006.05.028

James, M.R., Lane, S.J., Gilbert, J.S., 2000. Volcanic plume electrification: Experimental investigation of a fracture-charging mechanism. Journal of Geophysical Research, 105, 16,641–16,649. doi:10.1029/2000JB900068

Johnston, M.J.S., 1997. Review of electric and magnetic fields accompanying seismic and volcanic activity. Surveys in Geophysics, 18, 441–475. doi:10.1023/A:1006500408086

Jordan, T., Chen, Y., Gasparini, P., Madariaga, R., Main, I., Marzocchi, W., Papadopoulos, G., Sobolev, G., Yamaoka, K., Zschau, J., 2011. Operational earthquake forecasting: State of knowledge and guidelines for utilization. Annals of Geophysics, 54, doi: 10.4401/ag-5350.

Jouniaux, L., Pozzi, J.P., 1995. Streaming potential and permeability of saturated sandstones under triaxial stress: Consequences for electrotelluric anomalies prior to earthquakes. Journal of Geophysical Research: Solid Earth, 100, 10197–10209. doi: 10.1029/95JB00069

Junfeng Shen, Xuhui Shen, Qian Liu, Na Ying, 2010. The thermo-electric effect of magnetite and the mechanism of geo-electric abnormalities during earthquakes. Geoscience Frontiers, 1, 99–104. doi: 10.1016/j.gsf.2010.08.004

Kagan, Y.Y., 1997. Are earthquakes predictable? Geophysical Journal International, 131, 505–525. doi: 10.1111/j.1365-246X.1997.tb06595.x

Karakelian, D., Klemperer, S.L., Fraser-Smith, A.C., Beroza, G.C., July/August 2000. A transportable system for monitoring ultralow frequency electromagnetic signals associated with earthquakes, Seismological Research Letters, 71, 423–436, doi: 10.1785/gssrl.71.4.423

Kawase, T., Uyeda, S., Uyeshima, M., Kinoshita, M., 1993. Possible correlation between geoelectric potential change in Izu-Oshima Island and the earthquake swarm off the east Izu Peninsula, Japan. Tectonophysics, 224, 83–93. doi: 10.1016/0040-1951(93)90059-S

Lazaridou-Varotsos, M.S. (2013). Disastrous Athens earthquake, 1999. In Mary S. Lazaridou-Varotsos, *Earthquake Prediction by Seismic Electric Signals* (pp. 155-158). Springer Berlin Heidelberg.

Lazarus, D., 1993. Note on a possible origin for seismic electrical signals. Tectonophysics, 224, 265–267. doi: 10.1016/0040-1951(93)90079-Y

Published article: https://doi.org/10.1016/j.pepi.2020.106484

Li Xiangde, 1997. Influence of magnetism of diamond on its strength and the heat stability: Diamond and Abrasive Engineering, doi: cnki:ISSN:1006-852X.0.1997-02-000.

Lighthill, J., Sir, editor, 1996. A critical review of VAN: Earthquake prediction from seismic electrical signals: Singapore, World Scientific Publishing Co. Ptc. Ltd., 388 p.

Makarets, M.V., Koshevaya, S.V., Gernets, A.A., 2002. Electromagnetic emission caused by the fracturing of piezoelectrics in rocks. Physica Scripta, 65, 268–272. doi: 10.1238/Physica.Regular.065a00268

Maron, C., Baubron, G., Herbreteau, L., Massinon, B., 1993. Experimental study of a VAN network in the French Alps. Tectonophysics, 224, 51–81. doi: 10.1016/0040-1951(93)90058-R

Matsumoto, H., Ikeya, M., Yamanaka, C., 1998. Analysis of barber-pole color and speckle noises recorded 6 and a half hours before the Kobe earthquake. Japanese Journal of Applied Physics, 37, L1409–L1411. doi: 10.1143/JJAP.37.L1409

Midya, S.K., Gole, P.K., 2014. Variation of regional Gutenberg–Richter law parameter before and after large earthquakes in some earthquake prone zones around the world: Indian Journal of Physics, 88, 1227–1234. doi: 10.1007/s12648-014-0588-1

Ming Li, Lim, S.C., 2006. A rigorous derivation of power spectrum of fractional Gaussian noise. Fluctuation and Noise Letters, 6, C33. doi: 10.1142/S0219477506003604.

Mollo, S., Tuccimei, P., Heap, M.J., Vinciguerra, S., Soligo, M., Castelluccio, M., Scarlato, P. Dingwell, D.B., 2011. Increase in radon emission due to rock failure: An experimental study. Geophysical Research Letters, 38, L14304. doi: 10.1029/2011GL047962

Montgomery, D.R., Manga, M., 2003. Streamflow and water well responses to earthquakes. Science, 300, 2047–2049. doi: 10.1126/science.1082980

Mulargia, F., Marzocchi, W., Gasperini, P., 1996. Re−Rebuttal to the Reply of Varotsos et al. Geophysical Research Letters, 23, 1343–1344. doi: 10.1029/96GL01291

Papadopoulos, G.A., 2014. Communicating to the General Public Earthquake Prediction Information: Lessons Learned in Greece. In Wyss, M., Peppoloni, S. (Eds.) Geoethics: Ethical Challenges and Case Studies in Earth Sciences: Amsterdam, Elsevier, 450 p.

Papanikolaou, D., 1993. The effect of geological anisotropies on the detectability of seismic electric signals. Tectonophysics, 224, 181–187. doi: 10.1016/0040-1951(93)90071-Q

Park, S.K., Johnston, M.J.S., Madden, T.R., Morgan, F.D., Morrison, H.F., 1993. Electromagnetic precursors to earthquakes in the ULF bands: a review of observations and mechanisms. Reviews of Geophysics, 31, 117–132. doi:10.1029/93RG00820

Park, S.K., 1996. Precursors to earthquakes: seismoelectromagnetic signals. Surveys in Geophysics, 17, 493–516. doi:10.1007/BF01901642

Pham, V.N., Boyer, D., Chouliaras, G., Le Mouël, J.L., Rossignol, J.C., Stavrakakis, G.N., 1998. Characteristics of electromagnetic noise in the Ioannina region (Greece): A possible origin for so called “Seismic Electric Signal” (SES): Geophysical Research Letters, 25, 2229–2232. doi: 10.1029/98GL01593

Popov, K.V., Liperovsky, V.A., Meister, C.V., Biagi, P.F., Liperovskaya, E.V., Silina, A.S., 2004. On ionospheric precursors of earthquakes in scales of 2–3 h. Physics and Chemistry of the Earth, Parts A/B/C, 29, 529–535. doi: 10.1016/j.pce.2003.10.004

Pulinets, S.A., 1998. Seismic activity as a source of the ionospheric variability. Advances in Space Research, 22, 903–906. doi: 10.1016/S0273-1177(98)00121-5

Pulinets, S.A., Legen'ka, A.D., Gaivoronskaya, T.V., Depuev, V.K., 2003. Main phenomenological features of ionospheric precursors of strong earthquakes. Journal of Atmospheric and Solar-Terrestrial Physics, 65, 1337–1347. doi: 10.1016/j.jastp.2003.07.011

Pulinets, S.A., Boyarchuk, K.A., 2004. Ionospheric precursors of earthquakes: Berlin, Springer, 289 p.

Pulkkinen, A., Pirjola, R., Viljanen, A., 2008. Statistics of extreme geomagnetically induced current events, Space Weather, 6, S07001, doi:10.1029/2008SW000388

Raleigh, C.B., Healy, J.H., Bredehoeft, J.D., 1976. An experiment in earthquake control at Rangely, Colorado. Science, 191, 1230–1237. doi: 10.1126/science.191.4233.1230

Ramírez-Rojas, A., Flores-Márquez, E.L., 2013. Order parameter analysis of seismicity of the Mexican Pacific coast. Physica A: Statistical Mechanics and its Applications, 392, 2507–2512. doi: 10.1016/j.physa.2013.01.034

Rapoport, Y., Grimalsky, V., Hayakawa, M., Ivchenko, V., Juarez-R, D., Koshevaya, S., Gotynyan, O., 2004. Change of ionospheric plasma parameters under the influence of electric field which has lithospheric origin and due to radon emanation. Physics and Chemistry of the Earth, Parts A/B/C, 29, 579–587. doi: 10.1016/j.pce.2003.09.018

Roeloffs, E., 1999. Earth science: Radon and rock deformation. Nature, 399, 104–105. Retrieved from http://web.gps.caltech.edu/~avouac/publications/newsViewsRoeloffs.pdf

Sarlis, N., Lazaridou, M., Kapiris, P., & Varotsos, P., 1999. Numerical model of the selectivity effect and the V/L criterion. Geophysical Research Letters, 26(21), 3245-3248. doi: 10.1029/1998GL005265

Sarlis, N.V., Skordas, E.S., Lazaridou, M.S., Varotsos, P.A., 2008. Investigation of seismicity after the initiation of a seismic electric signal activity until the main shock. Proceedings of the Japan Academy. Series B, Physical and biological sciences, 84, 331–343. doi: 10.2183/pjab/84.331

Sarlis, N.V., Skordas, E.S., Varotsos, P.A., 2010. Nonextensivity and natural time: The case of seismicity. Physical Review E, 82, 021110. doi: 10.1103/PhysRevE.82.021110

Sarlis, N.V., Skordas, E.S., Varotsos, P.A., Nagao, T., Kamogawa, M., Tanaka, H., Uyeda, S., 2013. Minimum of the order parameter fluctuations of seismicity before major earthquakes in Japan. Proceedings of the National Academy of Sciences, 110, 13734–13738. doi: 10.1073/pnas.1312740110

Sarlis, N.V., Skordas, E.S., Varotsos, P.A., Nagao, T., Kamogawa, M., Uyeda, S. 2015. Proceedings of the National Academy of Sciences, 112 (4), 986–989. doi:10.1073/pnas.1422893112

Sarlis, N.V., Skordas, E.S., Varotsos, P.A. 2019. Geoelectric field and seismicity changes preceding the 2018 Mw6.8 earthquake and the subsequent activity in Greece. arXiv:1901.06658v3

Scoville, J., Heraud, J., Freund, F., 2015. Pre-earthquake magnetic pulses. Natural Hazards and Earth System Sciences, 15(8), 1873-1880. doi: 10.5194/nhess-15-1873-2015

Shannon, C.E., 1948. A mathematical theory of communication. The Bell System Technical Journal, 27, 379–423. doi: 10.1145/584091.584093

Shibkov, A.A., Zheltov, M.A., Skvortsov, V.V., Kol'tsov, R.Y., Shuklinov, A.V., 2005. Electromagnetic emission under uniaxial compression of ice: I. Identification of nonstationary processes of structural relaxation by electromagnetic signals. Crystallography Reports, 50, 994–1004. doi: 10.1134/1.2132409

Skordas, E.S., Sarlis, N.V., Varotsos, P.A., 2019. Identifying the occurrence time of an impending major earthquake by means of the fluctuations of the entropy change under time reversal. EPL, 128, 49001 (7 p). doi:10.1209/0295-5075/128/49001

Sneed, M., Galloway, D.L., Cunningham, W.L., 2003. Earthquakes: Rattling the Earth's plumbing system. US Department of the Interior, US Geological Survey. Retrieved from http://pubs.usgs.gov/fs/fs-096-03/

Sorokin, V.M., Chmyrev, V.M., Yaschenko, A.K., 2005. Theoretical model of DC electric field formation in the ionosphere stimulated by seismic activity. Journal of Atmospheric and Solar-Terrestrial Physics, 67, 1259–1268. doi: 10.1016/j.jastp.2005.07.013

Stacey, F.D., 1964. The seismomagnetic effect. Pure and Applied Geophysics, 58, 5–22. doi: 10.1007/BF00879136

Takahashi, I, Hattori, K, Harada, M, Yoshino, C., Isezaki, N., 2007. Anomalous geo-electrical signals observed at southern Boso Peninsula, Japan. Annals of Geophysics, 50, 123–135. doi:10.4401/ag-3092

Takeuchi, A., Nagahama, H., 2002. Interpretation of charging on fracture or frictional slip surface of rocks. Physics of the Earth and Planetary Interiors, 130, 285–291. doi: 10.1016/S0031-9201(02)00013-4

Tectonophysics, 1993. 224, 1–288. Retrieved from http://www.sciencedirect.com/science/journal/00401951/224/1

Thanassoulas, C., Tselentis, G., 1993. Periodic variations in the Earth's electric field as earthquake precursors: results from recent experiments in Greece. Tectonophysics, 224, 103–111. doi: 10.1016/0040-1951(93)90061-N

Thanassoulas, C., Klentos, V., Verveniotis, G., 2008. On a preseismic electric field "strange attractor" like precursor observed short before large earthquakes. [arXiv preprint] arXiv:0810.0242

Thomas, J.N., Huard, J., Masci, F., 2017. A statistical study of global ionospheric map total electron content changes prior to occurrences of M ≥ 6.0 earthquakes during 2000–2014.
Journal of Geophysical Research: Space Physics, 122, 2151–2161. doi:10.1002/2016JA023652

Tian, Z.X., Yan, J.X., Xiao, W., Geng,W.T., 2009. Effect of lateral contraction and magnetism on the energy release upon fracture in metals: First-principles computational tensile tests. Physical Review B: Condensed Matter and Materials Physics, 79, 144114, doi: 10.1103/PhysRevB.79.144114

Trique, M., Richon, P., Perrier, F., Avouac, J.P., Sabroux, J.C., 1999. Radon emanation and electric potential variations associated with transient deformation near reservoir lakes. Nature, 399, 137–141. doi: 10.1038/20161

Ulukavak, M., Yalçınkaya, M., Kayıkçı, E.T., Öztürk, S., Kandemir, R., Karslı, H., 2020. Analysis of ionospheric TEC anomalies for global earthquakes during 2000-2019 with respect to earthquake magnitude (Mw≥ 6.0). Journal of Geodynamics, 135, 101721. doi:10.1016/j.jog.2020.101721

Uyeda, S., 1996. Introduction to the VAN method of earthquake prediction *in* Sir James Lighthill, (Ed.), A Critical Review of VAN: Earthquake Prediction from Seismic Electrical Signals: Singapore, World Scientific Publishing Co. Ptc. Ltd., 388 p.

Uyeda, S., Kamogawa, M., Tanaka, H., 2009. Analysis of electrical activity and seismicity in the natural time domain for the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan. Journal of Geophysical Research, Solid Earth, 114, B02310, doi: 10.1029/2007JB005332.

Uyeda, S., Nagao, T., 2018. International Cooperation in Pre−Earthquake Studies: History and New Directions. In Pre−Earthquake Processes: A Multidisciplinary Approach to Earthquake Prediction Studies (pp. 1-6). Hoboken, NJ, USA: John Wiley & Sons, Inc. doi:10.1002/9781119156949.ch1

Varotsos, P., Alexopoulos, K., 1984a. Physical properties of the variations of the electric field of the earth preceding earthquakes, I. Tectonophysics, 110, 73–98. doi: 10.1016/0040-1951(84)90059-3

Varotsos, P., Alexopoulos, K., 1984b. Physical properties of the variations of the electric field of the earth preceding earthquakes. II. Determination of epicenter and magnitude. Tectonophysics, 110, 99–125. doi: 10.1016/0040-1951(84)90060-X

Varotsos, P., Alexopoulos, K., May 1987. Physical properties of the variations in the electric field of the Earth preceding earthquakes, III. Tectonophysics, 136, 335–339. doi: 10.1016/0040-1951(87)90033-3

Varotsos, P., Alexopoulos, K., Nomicos, K., Lazaridou, M., September 1988. Official earthquake prediction procedure in Greece. Tectonophysics, 152, 193–196. doi:10.1016/0040-1951(88)90045-5

Varotsos, P., Lazaridou, M., 1991. Latest aspects of earthquake prediction in Greece based on seismic electric signals. Tectonophysics, 188, 321–347. doi: 10.1016/0040-1951(91)90462-2

Varotsos, P., Alexopoulos, K., Lazaridou, M., 1993a. Latest aspects of earthquake prediction in Greece based on seismic electric signals, II. Tectonophysics, 224, 1–37. doi: 10.1016/0040-1951(93)90055-O

Varotsos, P., Alexopoulos, K., Lazaridou, M., 1993b. A reply to "Evaluation and interpretation of thirteen official VAN telegrams for the period September 10th, 1986 to April 28th, 1988," by Drakopoulis, J., Stavrakakis, G.N., Latoussakis, J.: Reply: Tectonophysics, 224, 237–250. doi: 10.1016/0040-1951(93)90076-V

Varotsos, P., Eftaxias, K., Vallianatos, F., Lazaridou, M., 1996a. Basic principles for evaluating an earthquake prediction method. Geophysical Research Letters, 23, 1295–1298. doi: 10.1029/96GL00905

Varotsos, P., Hadjicontis, V., Eftaxias, K., Skordas, E., Lazaridou M., 1996b. Reply to "Re-Rebuttal to the Reply of Varotsos et al.", by Mulargia, F., Marzocchi, W., Gasperini, P. Geophysical Research Letters, 23. 1345–1346. doi: 10.1029/96GL01288

Varotsos, P., Eftaxias, K., Lazaridou, M., Antonopoulos, G., Makris, J., Poliyiannakis, J., 1996c. Summary of the five principles suggested by Varotsos et al.[1996] and the additional questions raised in this debate. Geophysical Research Letters, 23, 1449–1452. doi: 10.1029/96GL01437

Varotsos, P., Eftaxias, K., & Lazaridou, M., 1996d. Reply to "A false alarm based on electrical activity recorded at a VAN−Station in northern Greece in December 1990," by Drakopoulos, J., Stavrakakis, G. Geophysical Research Letters, 23, 1359-1362. doi: 10.1029/96GL00911

Varotsos, P., Sarlis, N., Lazaridou, M., Kapiris, P., 1998. Transmission of stress induced electric signals in dielectric media. Journal of Applied Physics, 83, 60–70. doi: 10.1063/1.366702

Varotsos, P., Sarlis, N., Lazaridou, M., 1999. Interconnection of defect parameters and stress-induced electric signals in ionic crystals. Physical Review B, 59, 24–27. doi: 10.1103/PhysRevB.59.24

Varotsos, P., Sarlis, N., Skordas, E., 2001a. Magnetic field variations associated with the SES before the 6.6 Grevena-Kozani earthquake. Proceedings of the Japan Academy. Ser. B: Physical and Biological Sciences, 77(6), 93-97. doi: 10.2183/pjab.77.93

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2001b. Spatio-temporal complexity aspects on the interrelation between seismic electric signals and seismicity. Practica of Athens Academy, 76, 294–321. Retrieved from https://www.researchgate.net/publication/234077930_Spatio-temporal_complexity_aspects_on_the_interrelation_between_seismic_electric_signals_and_seismicity

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2002. Long-range correlations in the electric signals that precede rupture. Physical Review E, 66, 011902. doi: 10.1103/PhysRevE.66.011902

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2003a. Long-range correlations in the electric signals that precede rupture: Further investigations. Physical Review E, 67, 021109. doi: 10.1103/PhysRevE.67.021109

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2003b. Electric fields that "arrive" before the time derivative of the magnetic field prior to major earthquakes. Physical Review Letters, 91, 148501. doi: 10.1103/PhysRevLett.91.148501

Varotsos, P.A., 2005. The physics of seismic electric signals. Tokyo: Terrapub. 352 p.

Varotsos, P.A., 2007. Calculation of point defect parameters in diamond. Physical Review B, 75, 172107. doi: 10.1103/PhysRevB.75.172107

Varotsos, P., 2008. Point defect parameters in β-PbF2 revisited. Solid State Ionics, 179, 438–441. doi: 10.1016/j.ssi.2008.02.055

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., Lazaridou, M.S., 2008. Fluctuations, under time reversal, of the natural time and the entropy distinguish similar looking electric signals of different dynamics. Journal of Applied Physics, 103, 014906. doi: 10.1063/1.2827363

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2009. Detrended fluctuation analysis of the magnetic and electric field variations that precede rupture. Chaos: An Interdisciplinary Journal of Nonlinear Science, 19, 023114. doi: 10.1063/1.3130931

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2011a. Identifying long-range correlated signals upon significant periodic data loss. Tectonophysics, 503, 189–194. doi: 10.1016/j.tecto.2011.02.011

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., 2011b. Natural time analysis: The new view of time. Berlin, Springer-Verlag, 449 p.

Varotsos, P.A., Sarlis, N.V., Skordas, E.S., Lazaridou, M.S., 2013. Seismic Electric Signals: An additional fact showing their physical interconnection with seismicity. Tectonophysics, 589, 116–125. doi: 10.1016/j.tecto.2012.12.020

Varotsos, P.A., Sarlis, N.V., & Skordas, E.S., 2014. Study of the temporal correlations in the magnitude time series before major earthquakes in Japan. Journal of Geophysical Research: Space Physics, 119, 9192-9206. doi: 10.1002/2014JA020580

Varotsos, P.A., Sarlis, N.V., & Skordas, E.S., 2017a. Identifying the occurrence time of an impending major earthquake: A review. Earthquake Science. 30(4), 209–218. doi:10.1007/s11589-017-0182-7

Varotsos, P.A., Sarlis, N.V., & Skordas, E.S., 2017b. Natural Time Analysis of Seismicity in California: The epicenter of an impending mainshock. arXiv:1703.07378v2

Varotsos, P.A., Sarlis, N.V., & Skordas, E.S., 2019. Phenomena preceding major earthquakes interconnected through a physical model. Annales Geophysicae, 37, 315–324. doi:10.5194/angeo-37-315-2019

Wannamaker, P.E., Caldwell, T.G., Doerner, W.M., Jiracek, G.R., 2004. Fault zone fluids and seismicity in compressional and extensional environments inferred from electrical conductivity: the New Zealand Southern Alps and U. S. Great Basin. Earth Planets Space, 56, 1171–1176. doi: 10.1186/BF03353336

Wyss, M., 1996. Brief summary of some reasons why the VAN hypothesis for predicting earthquakes has to be rejected *in* Sir James Lighthill (Ed.), A Critical Review of VAN: Earthquake Prediction from Seismic Electrical Signals. Singapore, World Scientific Publishing Co. Ptc. Ltd., 388 p.

Xuhui Shen, Xuemin Zhang, Lanwei Wang, Huaran Chen, Yun Wu, Shigeng Yuan, Junfeng Shen, Shufan Zhao, Jiadong Qian, Jianhai Ding, 2011. The earthquake-related disturbances in ionosphere and project of the first China seismo-electromagnetic satellite. Earthquake Science, 24, 639–650. doi: 10.1007/s11589-011-0824-0

Yoshida, S., Clint, O.C., Sammonds, P.R., 1998. Electric potential changes prior to shear fracture in dry and saturated rocks. Geophysical Research Letters, 25, 1577–1580. doi: 10.1029/98GL01222

Zhao Chao, Shen Jun-feng, Zhang Zi-li, Fu Wen-jing, 2012. Thermoelectricity of magnetite-containing rocks and its implications for seismology: Journal of Mineralogy and Petrology, 1, 003. Retrieved from http://en.cnki.com.cn/Article_en/CJFDTOTAL-KWYS201201003.htm

Zhu, F., Su, F., Lin, J., 2018. Statistical analysis of TEC anomalies prior to M6. 0+ earthquakes during 2003–2014. Pure and Applied Geophysics, 175(10), 3441–3450. doi:10.1007/s00024-018-1869-y

Zlotnicki, J., Cornet, F. H., 1986. A numerical model of earthquake−induced piezomagnetic anomalies. Journal of Geophysical Research: Solid Earth (1978–2012), 91(B1), 709–718. doi: 10.1029/JB091iB01p00709