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Analysis of argon concentration anomalies in underground water in Kamchatka (Russia) (*)

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Summary. — In this paper we present the results of characterising time series of the argon content of groundwater recorded in the Kamchatka area of Russia. The problems of correlating anomalies in the argon data with seismic activity are explored. A new statistical technique for relating anomalies to geophysical observations based on Markov Chain Monte Carlo modelling methods is outlined.

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1. – Introduction

In over 100 years of research, deterministic earthquake (EQ) prediction has still not been satisfactorily demonstrated, despite the wide variety of techniques that have been investigated. On the one hand, it is widely thought that the chaotic, highly non-linear nature of earthquakes may mean that short term prediction is unrealisable although less specific, longer term forecasting remains a possibility [1, 2]. On the other hand, the "anomalous" geophysical signals recorded by experimental scientists before some earthquakes are real measurements that are not easily explicable in terms of random processes such as noise. The possibility remains that these signals might somehow be used to improve the warning of impending EQs but there are several problems confronting those trying to pursue this research line. There is the difficulty of

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collecting a data series of sufficient duration for an anomaly to be defined unambiguously with respect to the normal statistical fluctuations in the data. A more difficult problem is to prove in some objective way that these anomalies are related to the stresses and strains that build up in advance of EQs, and that they have real predictive power.

One of the most consistently promising techniques over the last century has been the analysis of hydrochemicals in groundwater from sources such as wells and springs. There are a number of obvious mechanisms that could link seismic activity (and associated geological stress) with the increase in the chemical content and flow rate of water percolating underground. In some cases subjective observation of the data suggests that there might be evidence for co-seismic and post-seismic effects, but how good is the evidence for any statistically significant pre-seismic effects? And how can any such evidence be assessed in an objective and quantifiable way? In order to address these questions we have analysed some of the best data sets available—up to 20 years of data recorded in the Kamchatka region of eastern Russia where the ion and gas content of three geographically separated groundwater sources have been measured regularly every 3 days [3].

2. – The time series data

The Kamchatka peninsula is an active volcanic area in the far East of Russia. Frequent earthquakes occur along a nearby offshore subduction zone with hypocentral depths ranging from a few kilometres to 500 km. At sites near the city of Petropavlovsk, natural and artificial springs have been sampled roughly every three days and the dissolved gas and ion content analysed. Recordings at the first site—a natural spring at the foot of an active volcano—began in January 1977. At a second and third site, both deep artificial wells, measurements began in 1986 and 1992, respectively. In the period 1977 to 1986 there was no major seismic activity and magnitudes did not exceed 6.0; this can be regarded as excellent training data to study the normal fluctuations in the observations.

In the second ten years, from 1986 to date, there have been five main seismic events with magnitudes $M \geqslant 6.5$ and a number of smaller events. Two of these EQs occurred in 1996, the first in January 120 km to the North of Petropavlovsk followed by a shallower event in June to the South East in the subduction zone. These 1996 EQs are the main focus of this study.

3. – Data processing

The analysis presented here is based on a time series of seismic information and one of argon concentration values. The seismic time series contained geographical information that enabled the effect of each event on the area around the spring to be calculated through the seismic stress parameter. For $M < 5$ the value of this parameter ε can be found from $\varepsilon = 10^{(1.5M\text{-}9.18)}/R^3$, otherwise $\varepsilon = 10^{(1.3M\text{-}8.19)}/R^3$, where M is the magnitude and R (km) is the epicentral distance from the EQ to the centre of the measurement sites. Figure 1a shows a plot of all the values $\varepsilon \geqslant 0.001$ and fig. 1b shows the raw argon data collected from spring 2. The time scale along the bottom of all the figures represents days since 1/1/1960 and in the case of fig. 1 the axis runs from the start of 1988 to the end of April 1997.

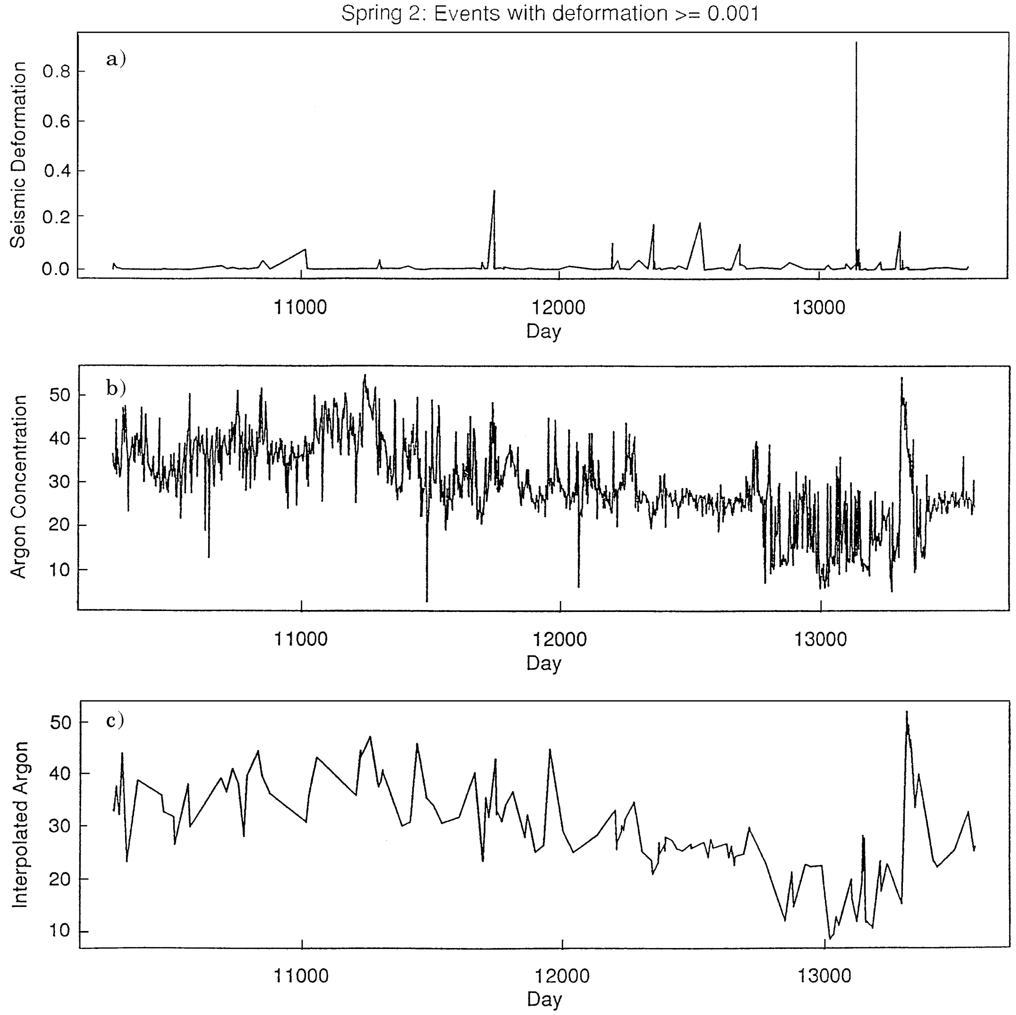


Fig. 1. – (a) Seismic deformation parameter ε for the period 1988-1997 for values greater than 0.001. (b) Measured argon concentrations for Spring 2 for the same period. (c) Time series b) interpolated to the instants of the seismic events. The units for argon concentration are millilitre/litre $\times 10^{-2}$. Time is in days since 1/1/1960.

A difficulty in comparing the time series 1a and 1b is that the times when argon samples were taken do not correspond to the instants when seismic events occurred; a direct correlation between the two is therefore not possible. To circumvent this problem we linearly interpolated the argon data to exactly the times of the seismic events, see fig. 1c, and then correlated the two series. Over the whole data set the coefficient of correlation between ε and the interpolated argon is -0.086 indicating that the two series are unrelated, but there are events towards the end of the figure in 1996 that appear to be more interesting when a large increase in argon content appears to occur at roughly the same time as a seismic event in June 1996.

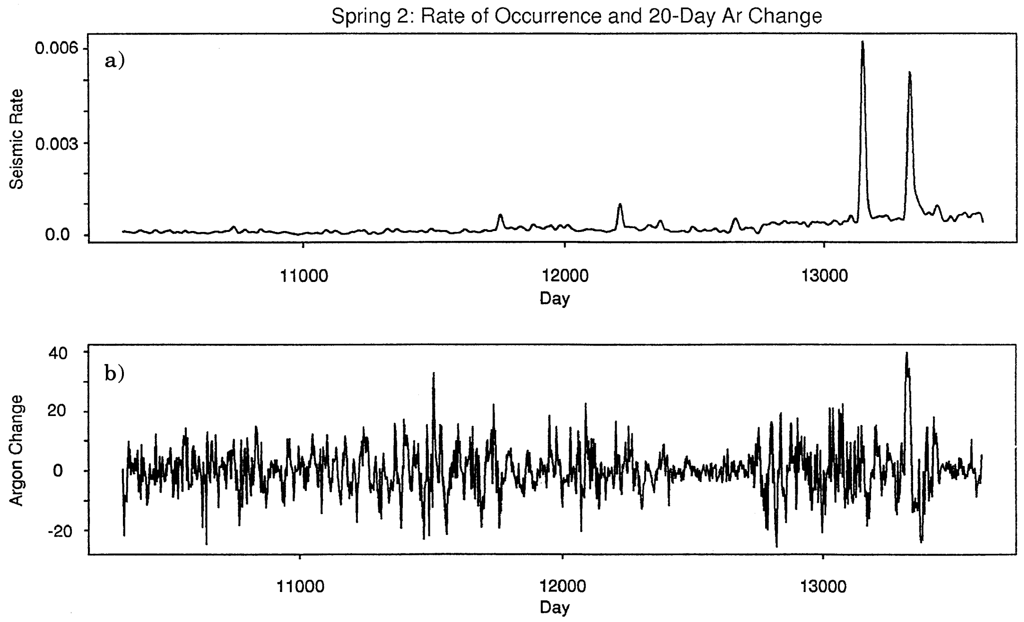


Fig. 2. – Rate of occurrence of seismic events and the 20 day change in the argon concentration of groundwater for Spring 2. Time is in days since 1/1/1960.

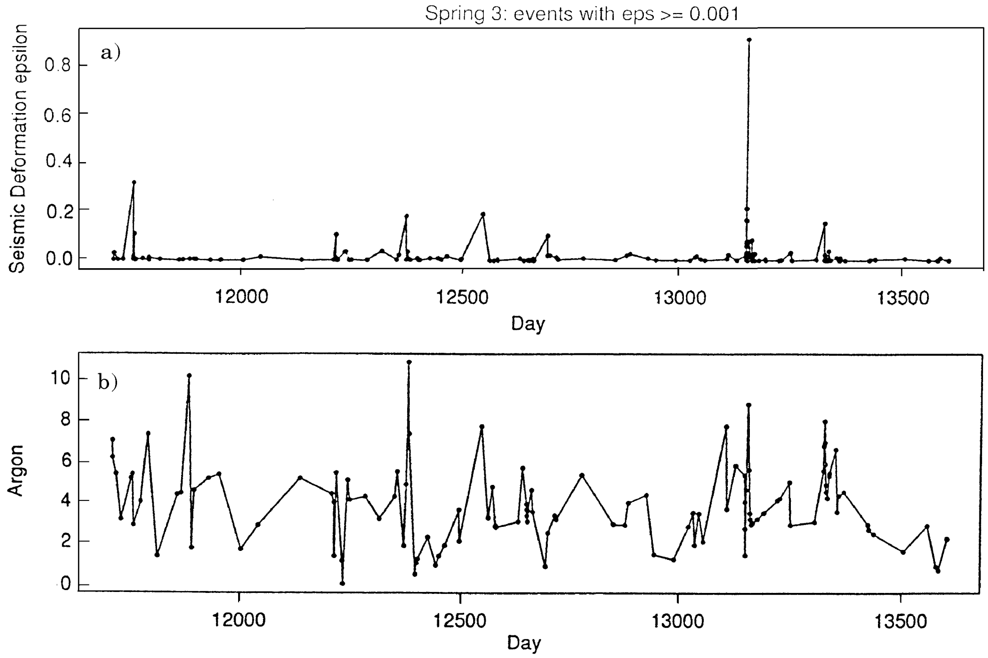


Fig. 3. – Seismic events with $\varepsilon \geqslant 0.001$ and the argon data for Spring 3. Time is in days since 1/1/1960.

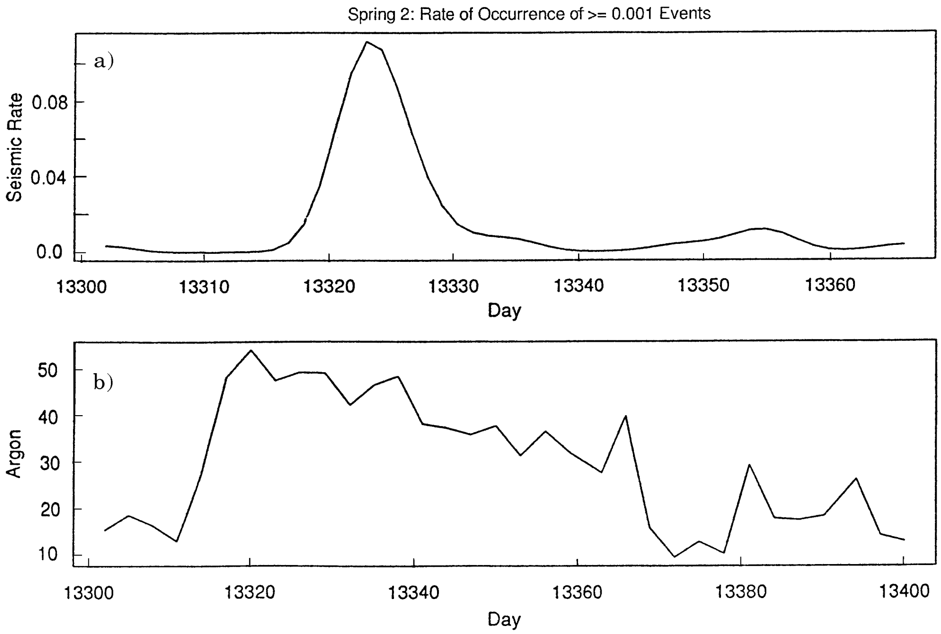


Fig. 4. – A short section of data expanded from fig. 1. The correlation coefficient between these two time series is 0.526 as compared to – 0.086 for all the data shown in fig. 1.

In figs. 2a and b we have plotted the rate of occurrence of seismic events against the 20-day change in argon concentrations. The second of the 1996 EQs appears the larger in occurrence rates of fig. 2a, even though its magnitude was smaller, because it was composed of many small seismic events. This event was preceded by a sudden increase in the rate of change of argon. A similar effect is shown in fig. 3 where the upper trace is the same ε plot as before but the bottom trace is the argon concentration measure at spring 3. Again, a large increase in the groundwater argon concentration occurs at the time of the two large EQ events of 1996.

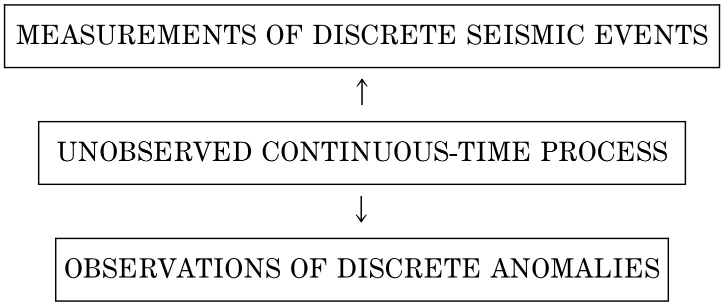
We must be careful in our analysis though; note that around 11500 days in fig. 2b and 11800 days in fig. 3b there are also sudden increases in the argon that do not correspond to any seismic activity. As a demonstration of how misleading data presentations can be, we have plotted in fig. 4 a short section of about 100 days data from spring 2. The cross-correlation of the seismic rate in fig. 4a and the argon in 4b gives a coefficient of 0.526 which would appear to be convincing. And yet this is part of the same data set that gave an overall coefficient of – 0.086. By being selective we can achieve just about any result we want.

How then are we to demonstrate objectively whether or not these anomalies are related to EQ activity?

4. – A statistical approach to the problem

Suppose seismic events are observed at times and magnitudes (τ_i, m_i), $\{i = 1, \ldots, n\}$ and the claimed precursors are observed at times and magnitudes (t_j, c_j),

$\{j = 1, \ldots, k\}$. The problem then is to establish objectively the presence or absence of a relationship between (t_j, c_j) and (τ_i, m_i). One method of doing this is to assume that both the seismic events and the precursor observations are (potentially) related to an unobserved process $S(t)$ which we might call "stress", as shown below:



The times of the occurrences and magnitudes of seismic events can be modelled by a marked Poisson process in (τ, m)-space with intensity function S:

$$\text{Expected no. of points in } (\tau, \tau + \mathrm{d}\tau) \times (m, m + \mathrm{d}m) = E(N(\mathrm{d}t, \mathrm{d}m)) = \lambda(S(t), m)\, \mathrm{d}\tau\, \mathrm{d}m$$

for some function λ. Suppose also that the putative precursor values c are related to S by

$$c_j\,(= c(t_j)) = S(t_j) + Y_j,$$

where the Y_j $\{j = 1, \ldots\}$ represent random noise in the relationship.

If we assume a time series co-variance structure for S and an explicit functional form for λ, then we can fit the model by Markov Chain Monte Carlo methods with the precursor data contributing to the fit of the covariance structure. The absence of a relationship between claimed precursors and the times and/or magnitudes of seismic events would correspond to $\lambda(S(\tau), m)$ in fact not varying with $S(\tau)$. This can be tested objectively from the fitted results.

In this way the S process bridges the gap between the times τ_i of EQ events and the times t_j of observations of the precursor. This formulation is general in the sense that c_j could be any function of direct measurements on some physical quantity such as argon concentration at t_j or $(t_j - l)$, where l is some lag in time. We believe this approach has sufficient rigour to meet IASPEI (International Association for Seismology and Physics of the Earth's Interior) guidelines for analysing and claiming potential EQ precursor phenomena.

5. – Conclusions

The argon content of groundwater recorded in Kamchatka data suggests the possibility of a co-seismic response to a shallow earthquake in the subduction zone off the Eastern seaboard. When analysing the data, it was found more useful to compare the rate of change of argon concentration with the frequency of the seismic events. These dynamic parameters appear to be more revealing than the absolute values recorded.

An interpolation method of overcoming the differences in instantaneous times between the EQ events and the argon recordings has been used, but the dangers of being too selective in the data being correlated (to improve the correlation coefficient) are all too apparent.

A new statistical method of analysis is put forward that attempts to compare EQ and potentially anomalous geophysical data in a more rigorous and objective way through an unobserved stress process. This approach can quantify the relationship and help to meet IASPEI guidelines for those working in this research field. A new technique of this kind is needed if we are to move on and investigate claimed pre-seismic, rather than co-seismic, geophysical behaviour that might be used for EQ prediction.

It must be remembered, however, that even if some anomalous hydrogeochemical behaviour is shown to be precursory to an earthquake it will not necessarily have any useful predictive power because there are many other issues to consider, especially the false alarm rate [4, 5].

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