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Seismogeochemical algorithms for earthquake prediction: an overview

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Abstract
While the literature abounds with case histories related to geochemical precursory phenomena, only a few studies on definite seismogeochemical algorithms have been published so far. Currently, available theoretical algorithms are based on obsolete views of fluid migration processes that do not take into account the possibility of rapid and long-distance gas migration from the focal zone. Empirical algorithms are often based on a limited number of data and need validation for several geostructural environments. The algorithms of Sardarov (1981) and Rikitake (1987), for Rn and other geochemical elements, suggest that a definite relationship exists between geochemical parameters and seismic events. Their validation must be based on the verification of independence (maintained by the former author) or dependence (maintained by the latter) of the precursor time on the seismic data.

Key words *earthquake prediction – fluid geochemistry – fluid migration*

1. Introduction

Although there are many published studies on geochemical precursors to seismic activity, both reporting the detection of validated precursory phenomena (*e.g.*, Sugisaki, 1985; Wakita *et al.*, 1988; Igarashi *et al.*, 1995; Tsunogai and Wakita, 1995) and discussing theory or general reviews (*e.g.*, Thomas, 1988), very few works define the quantitative relations between geochemical data and seismic data.

In 1990 the IASPEI Sub-commission on earthquake prediction (Wyss, 1990) stated that the earthquake precursor research still has a long way to go to become useful. Basically, geochemical observation is still at the stage of accumulating data and searching for parameters effective in detecting precursory phenomena. Detailed fluid geochemistry studies of selected seismogenic areas and a multiparametric approach of the geochemical-hydrological continuous monitoring systems are necessary to formulate and test empirical seismogeochemical algorithms. Furthermore, recent studies point out the importance of the stress redistribution (Stein *et al.*, 1994; King *et al.*, 1994) and pore pressure evolution at seismogenic depth (Fournier, 1991; Nur and Walder, 1992; Linde *et al.*, 1994; Miller *et al.*, 1996) in triggering seismicity. In fact, local and regional settings are important in influencing and determining the occurrence and the pattern of the geochemical anomalies. Up to now, however, no work in international literature has dealt exhaustively with this point. These factors should be considered in the formulation of new seismogeochemical algorithms.

In this paper the fundamentals of seismogeochemical algorithms and proposed formulae are discussed. Theoretical basis for the construction of algorithms is briefly reviewed.

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2. Fundamentals

The research on seismogeochemical algorithms is aimed at defining quantitative relations between seismic parameters, such as earthquake magnitude and epicentral distance, and geochemical anomalies occurring in mobile systems (*i.e.*, subsurface gas and groundwater) with endogenetic components. Such relations can be formulated in two ways:

– Theoretically, *i.e.*, defining and underlying a theoretical physical model describing the interaction of the mechanical processes preceding an earthquake within a geochemical domain.

– Empirically, *i.e.*, identifying patterns in geochemical variations that characteristically occur prior to significant earthquakes.

Both ways generally involve the following main geochemical and seismic parameters:

Geochemical data

A = anomaly amplitude
F_a = anomaly frequency
t_a = anomaly duration.

Seismic data

M = main shock magnitude
R = epicentral distance from observed site.

The time between the anomaly outset and the main shock is named «precursor time», t_p. It may be included in the algorithm as a geochemical datum (*e.g.*, Rikitake, 1987). The general form of a seismogeochemical algorithm is therefore:

$$A,\ F_a,\ t_a,\ t_p = f(M, R). \qquad (2.1)$$

However, some Russian researchers claimed that the precursor time is practically independent of the magnitude or epicentral distance of the impending earthquake (*e.g.*, Sardarov, 1981). This time is characteristic of the given region (*i.e.*, geologic environment) and the prediction technique (*i.e.*, type of measurement) being employed. Therefore predictive algorithms should not consider the parameter t_p. This is in contrast with those reported by Barsukov *et al.* (1985b) and Rikitake (1987).

Up to now, geochemical anomalies have referred to the value of one of the following parameters measured in groundwater:

- *physicochemical parameters* (pH, Eh, temperature, conductivity),
- *gas concentration* (mainly Rn, He, CO_2, H_2, CH_4, H_2S),
- *ionic content* (Cl^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}),
- *trace compounds* (boron, mercury, arsenic, etc.),
- *isotopic ratios* ($^3He/^4He$, $\delta\,^{13}C_{(CO_2,\,CH_4)}$; δD, $\delta\,^{18}O$, $^4He/^{40}Ar$, $\delta\,^{32}S_{(H_2S)}$, $^{234}U/^{238}U$, $^{220}Rn/^{222}Rn$),

and to the concentration in soil-air and gas vents of several gaseous elements and compounds such as Rn, He, H_2, CO_2, CH_4, H_2S.

Among these parameters two groups of hydrogeochemical precursors may be distinguished (Barsukov *et al.*, 1985b):

a) Trace and major chemical components: they have high stability of content in seismically quiescent periods (variations on the background < 2-7%) but are less effective as precursor tools due to the lack of effective analytical techniques for continuous monitoring.

b) Gaseous components: they have a pulse nature in seismically quiescent periods (variations on the background up to 15-40%), may be affected by solar-lunar tides, but are more effective as precursor tools.

Basically, most of the works on geochemical precursors refer to gas (mainly Rn, He and H_2) and physicochemical parameters (temperature, electrical conductivity, etc.).

3. Collection and time series analysis of geochemical data

The fundamental assumptions made in the algorithm studies are:

– The geochemical parameters examined in the fluid phases are consistent indicators of the processes occurring in the focal zone of an impending earthquake.

– Observed variations in those parameters are related to actual physical, chemical and

thermodynamical changes in the region surrounding the focal zone.

Often none of these assumptions is true. Anomalous variations in geochemical data are not necessarily precursors of seismic events and they can occur without the subsequent occurrence of an earthquake. The geochemical data are often biased and the interpretation of geochemical signals as earthquake-linked anomalies are generally susceptible to criticism since, in actual use, the following guide-lines are not always respected:

– Geochemical data should be provided by a geochemical monitoring network, which may also allow cross-correlation analyses (often only one monitoring station is used).

– Geochemical background and geological-hydrogeological boundary conditions should be known in detail.

– Geochemical monitoring should be continuous and not discrete.

– Long-term monitoring data should be available.

– Geochemical data should be compared with geophysical ones.

– Each station should be able to monitor both endogenic and exogenic (*i.e.*, atmospheric) parameters.

– Monitoring networks should be characterised by instrumental uniformity (*i.e.*, monitoring standardisation).

Basically, geochemical anomalies in time series are not only related to the processes of the development of an earthquake but also to many aseismic factors (*e.g.*, the pulse-nature of gas outflow) and they may be affected by climatic, astronomical and anthropogenic factors. To use a geochemical parameter to formulate an algorithm it is necessary to estimate its informational stability and the statistical range of the anomalous changes as well as to define an «anomaly» criterion. Moreover, a detailed knowledge of the geological and geochemical setting of the monitored area is essential; recent literature just stresses the importance of the «sensitivity» factor of a given area (*e.g.*, Kümpel, 1992).

Any effort to develop a seismogeochemical algorithm must first unravel the anomalous data in the observed time series and then correlate their occurrence with subsequent earthquakes. The discrimination of the anomalies is generally done on a statistical basis (*e.g.*, Barsukov *et al.*, 1985a). True geochemical precursors can also be observed by analysis of the spectral properties of a chemical concentration time-series. An example of sequence analyses is that performed by Barsukov *et al.* (1987) on helium data. The authors assumed that the earthquake build-up focus produces oscillations at an increasing frequency. The borehole (monitoring point) may be a resonator sensitive to those vibrations. The build-up of each seismic event causes a series of anomalies in the helium level, each as increases in the amplitude of the helium level at a particular frequency – the resonant frequency for the geochemical system. In the initial studies the authors found correlations between helium signals and seismic events but subsequent works (Belyayev *et al.*, 1990) showed that monitoring errors and aseismic phenomena (seasonal and climatic fluctuations) significantly perturb the parameters involved in the frequency analysis.

Basically, the propagation, spread and production of transient signals of a physical and geochemical nature is a function of the structure of the embedding geological environment. Due to the heterogeneity of the geological environments, it is more surprising – than a rule – that a kind of sorting or establishment of different reaction-precursor categories is possible for each seismogenic area, taking into account the strandpoints of the recently enhanced seismology related disciplines such as fault zone rheology, fluido-dynamics, stress-field recognition methodologies, fluid geochemistry, paleoseismology, etc. Therefore, for different geotectonic domains perhaps different classes of approaches should be applied.

4. Theoretical algorithms

Theoretical algorithms are based on the assumption that variations of geochemical parameters of subsurface fluids are related to changes in physical processes occurring in the lithosphere.

The primary problem is that the lithosphere is an unstable and non-linear system; consequently it is very difficult to establish a definite model of interaction between rock fracturing/dislocation motion and geochemical behaviour of crustal fluids. There is no *consensus* on the type or number of geochemical parameters that may be sensitive to earthquake preparation mechanisms, or any universal opinion on the mechanisms responsible for geochemical anomalies.

The best review and comment on the mechanisms of geochemical anomaly generation are those of Thomas (1988). He discusses the main processes proposed, that are:

1) Physicochemical release by Ultrasonic Vibration (UV model).

2) Chemical release due to Pressure Sensitive Solubility (PSS model).

3) Physical release by Pore Collapse (PC model).

4) Chemical release by microfracturing (or Increased Reactive Surface Area, IRSA model).

5) Physical mixing due to Aquifer Breaching/Fluid Mixing (AB/FM model).

The first model suggests that loosely bound elements and compounds in subsurface rocks can be mechanically freed by ultrasonic vibrations due to earthquake-linked fracturing (*e.g.*, Barsukov *et al.*, 1985b). The second model refers to the possibility that precursory stress changes can increase the solubility of ion and gas and consequently their concentration in water (*e.g.*, Cai *et al.*, 1984). The third model considers that at increasing stresses prior to an earthquake the pre-existing pore volume collapses and expels pore fluids into the circulating groundwater, generating an anomaly (*e.g.*, Fleischer and Mogro-Campero, 1985).

Such three models are, however, highly questionable as they require driving-forces generally larger than those expected for large shock-linked anomalies.

Thomas (1988) claimed that the models which seem best able to account for reported geochemical anomalies are the IRSA and AB/FM models. Basically, pervasive microfracturing of rocks linked to stress-strain propagation from focal zone (*e.g.*, Scholz *et al.*, 1973; Anderson and Grew, 1977; Hauksson, 1981) and fracturing of hydrologic barriers between isolated aquifers allow different fluids to mix (*e.g.*, Sibson, 1981; Barsukov *et al.*, 1985b) explaining a wide range of precursor anomalies.

Microfracturing models can vary (see the Dilatancy-Diffusion model of Scholz *et al.* 1973 and the Avalanche Fracturing model of Myachkin *et al.*, 1975) but all must take into account the mobility of two components:

– Rheologic component, *i.e.*, the mechanics of rock fracturing/dislocation and the propagation of the strain field.

– Fluidodynamic component, *i.e.*, the migration and behaviour of gas and/or groundwater.

The shock-linked effect (or seismic signal) from the focal zone to the monitoring zone may be given by two mobile components (fig. 1): fluids and strain-field. Observations over recent years have been interpreted as implying that earthquakes have had effects on gas concentrations at large distances from the hypocentres. A physical model must therefore explain such long-range effects.

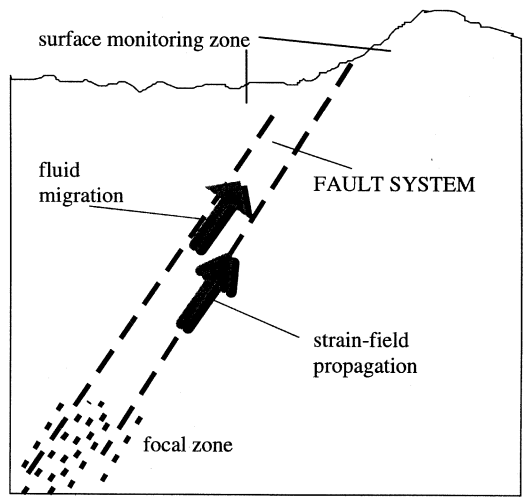

Fig. 1. The seismic signal, from the focal zone to the monitoring zone, may be given by the combination of two mobile components: fluids (gas and/or water) and strain-field.

The long-range effect can be considered as due to a combination of:
- a Long-Range Fluid Migration (LRFM);
- a Long-Range Strain Propagation (LRSP).

In the first case the pre-seismic stress induces a rapid movement of fluids (*e.g.*, squeezing) far from the future focal zone, *i.e.*, the vehicle of the stress signal is gas or water migrating to the surface. Such a process has also been termed «seismic pumping» (Sibson *et al.*, 1975).

In the second case the strain field propagates toward geochemical domains (*e.g.*, gas in faults, aquifers, fluids pockets) far from the focal zone. In this case the fluid migration is limited to near-surface fluid-rock processes, close to the monitoring zone.

The possibility of LRSP is universally accepted by the seismological community. On the contrary the migration of gas in the subsurface has not been sufficiently studied. Currently available migration models are based on laboratory studies and computer codes (*e.g.*, Ortiz *et al.*, 1997) which include a wide number of physical variables that, however, do not sufficiently take into account phenomena over geologic time and space scale, *i.e.*, processes occurring in real geologic scenarios. The reason for this is due to minimal field data on gas behaviour in the geologic environments. Basically there is no a universally accepted view of the main migration mechanisms of subsurface gas.

In the 70's and 80's seismogeochemical models were defined postulating gas migration by diffusion or groundwater transport, namely relatively slow migration processes. No long-range rapid fluid migration mechanisms (LRFM) were considered. Consequently long-distance earthquake effects were related to LRSP only (*e.g.*, Fleischer, 1981; Friedmann, 1985). A typical conclusion often reported in older literature is that reported by Hauksson and Goddard (1981):

«Based on the groundwater travel time arguments and the large distance between the epicentre and the monitoring well relative to the size of the forthcoming rupture zone, it is suggested tentatively that the observed Rn anomalies resulted from changes in the immediate vicinity of the well, rather than at the distant focal region. To accomplish this it is necessary to assume that changes in stress and strain are propagated from the forthcoming rupture zone to the monitoring station».

Even if the last sentence is right, the LRFM cannot be disregarded *a priori*. But Hauksson and Goddard, like many of their colleagues, did not know at that time about the possibility of LRFM, as suggested more recently by several authors (*e.g.*, Malmqvist and Kristiansson, 1984; Hermansson *et al.*, 1991; Durrance and Gregory, 1990; Etiope and Lombardi, 1995, 1996). Nowadays transport models assign greater importance to the role of advecting free-phase gas (in saturated or dry media) than to the role of diffusion or groundwater migration. Even in seismologic studies the rapid and long-distance movements of free gas – including Rn – have assumed greater importance than those of gas dissolved in groundwater (*e.g.*, Zhang *et al.*, 1994). Unfortunately no algorithms based on LRFM have been proposed so far.

Based on LRSP, some papers report theoretical relations between earthquake magnitude and maximum epicentral distance at which geochemical anomalies have been observed. The main ones are:

$$R = 10 \exp 0.43\, M$$
(Dobrovolsky *et al.*, 1979)

$$R = (10 \exp 0.813\, M)/1.66 \text{ for } M < 3$$
(Fleischer, 1981)

$$R = (10 \exp 0.480\, M)/1.66 \text{ for } M > 3$$
(Fleischer, 1981)

where R is the distance (km) between the epicentre and the monitoring site and M is the impending earthquake magnitude. But such relations do not relate geochemical parameters to seismic ones (both R and M are seismic data) and therefore formally they cannot be considered seismogeochemical algorithms. They only provide an estimate of the range of possible detection of geochemical anomalies as a function of the seismic magnitude; thus, they are useful to select earthquakes – satisfying any one of the formula – which can produce geochemical anomalies in a given monitoring zone.

5. Empirical algorithms

Empirical algorithms are based on the statistical comparison of geochemical data with seismic ones, from an existing data base. Attempts have long been made to find mathematical relations between geochemical time series regarding gas and groundwater parameters and the occurrence of seismic events. Studies have been fragmentary and unsystematic and the results obtained were ambiguous and controversial. Nevertheless, the empirical algorithm represents a unique tool to predict earthquakes without requiring an understanding of the rock-mechanics – fluid geochemistry interactions. Up to now there has been no model univocally linking earthquakes and geochemical anomalies, meaning that the validity of the proposed models is not yet proved. The definition itself of *experimental* algorithms points out that it is based on (field) observation. Most of the algorithms owe their existence to a statistical approach (from geochemical data bases). The interactions between *experimental* algorithms and physical theories appear (sometimes) to occur in a successive step.

An empirical relation (modified by Sugisaki, 1985 from Hauksson, 1981) between epicentral distance and earthquake magnitude is:

$$R = (10 \exp 0.47\ M)/1.97. \qquad (5.1)$$

It results from a worldwide data set (91 radon anomalies) of precursory signals in the U.S.A., the former U.S.S.R., China, Japan and Iceland. However, this formula, like those discussed in the previous section, is not a true seismogeochemical algorithm (it does not relate explicitly geochemical and seismic variables). It only gives the maximum distances to which radon changes are likely to be encountered.

Real seismogeochemical algorithms were reported only by Sardarov (1981), Barsukov *et al.* (1985b) and Rikitake (1987).

5.1. *The Sardarov-algorithm*

Based on 535 cases of seismically produced changes in the chemical composition of deep waters and natural gases in ex U.S.S.R. and Japan, Sardarov (1981) defined the empirical relationship:

$$a = K e^{M}/R \qquad (5.2)$$

where a is the ratio of the largest value (positive or negative fluctuation) of the geochemical parameter to the mean value of its background fluctuations, M is the magnitude, R is the epicentral distance and K is a dimensional factor (km). The considered predictive forerunners were the concentration of radon, hydrogen, methane, nitrogen, helium and argon in natural gases, plus the electric conductivity of deep waters during seismically quiescent periods. The author claimed that using a obtained from several monitoring stations (preferably four) it is possible to estimate R before, and M then, by using two nomograms (Sardarov, 1981).

For the simplest case of two stations (providing a_1 and a_2) spaced at a distance B and placed on a straight line with the epicentre, the difference $\Delta a = a_1 - a_2$ satisfies the equation:

$$\log a_1 = \log \Delta a + \log (R/B + 1). \qquad (5.3)$$

A first nomogram makes it possible to derive R from known values of a_1 and Δa. Knowing R and a and using a second nomogram it is possible to estimate the magnitude of the earthquake. Data from many other Russian researchers suggest that such an algorithm is sufficiently versatile and applicable for various geochemical parameters observed in different parts of the world.

5.2. *The Barsukov-algorithms*

Barsukov *et al.* (1985b) reviewed geochemical data, as predictive tools, on statistical basis. They reported the following equations:

$$\log (R\, t_p) = 0.63\ M \pm 0.15 \qquad (5.4)$$

$$I_b = K\sqrt{S_b} \qquad (5.5)$$

where $K = \log E$.

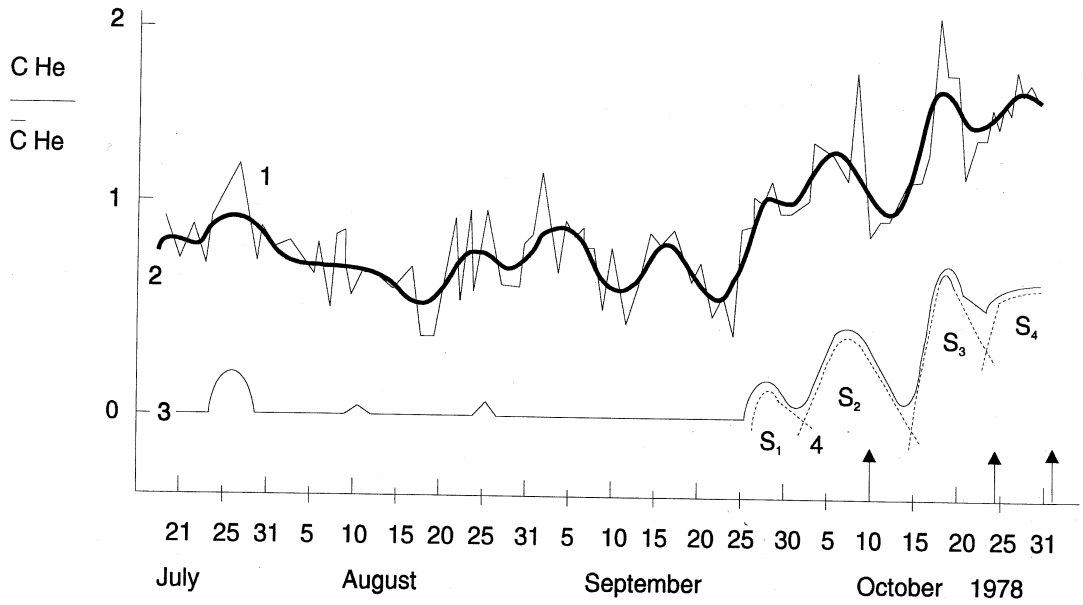

Fig. 2.. Variation in concentration of helium in Yavroz well waters in the period before the earthquakes at Osh, Afghan and Alai. Tha data were used in the development of the earthquake algorithm. 1) Helium concentration relative to mean value. 2) Helium concentrations averaged by means of the Spencer formula. 3) Helium variations, background excluded. 4) «Bells» for estimating earthquake intensity and time. S_1, S_2, S_3 and S_4 are areas of the bells in artificial units (redrawn from Barsukov *et al.*, 1985a).

The formula (5.4) relates precursor time (t_p, days) to magnitude and epicentral distance (R, km) on the basis of the data for variations in concentration of the gaseous components recorded in the Tashkent precursor study area during 1974-1980. This algorithm is not coherent with the experience, reported by other authors (*e.g.*, Sardarov, 1981), of the independence of t_p to seismic parameters. If the relation between t_p and M, R depends only on the geologic system and the type of monitoring, this relation is valid only for the cases studied.

The formula (5.5) is based on observations of helium variations in the Yavros flowing-well waters (Dushanbe study area, former U.S.S.R.); K is the energy class on an earthquake, E is the energy release in Joules in the earthquake focus, I_b is the earthquake intensity (according to Richter's scale) and S_b is the area of the unit «bell» under the background-corrected time-dependence curve of helium concentration (fig. 2). The authors claimed that the AF (Avalanche Fracture) model of Myachkin *et al.* (1972, 1975) is congruent with the geochemical precursor data. Nevertheless they reported some ambiguous relationships between anomalies and seismic events.

5.3. *The Rikitake-algorithm*

On the basis of 14 radon data sets Rikitake (1987) reported the following relation between precursor time and main shock magnitude (fig. 3):

$$\log t_p = (-0.47 \pm 0.73) + (0.28 \pm 0.12)\, M. \qquad (5.6)$$

This formula is based on the general algorithm form: $\log t_p = a + bM$, a linear equation that

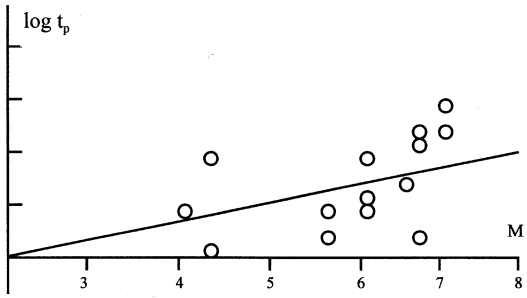

Fig. 3. Log t_p-M relation for radon concentration and other geochemical elements (redrawn from Rikitake, 1987).

holds well for all the precursor disciplines. But even this equation is in contrast with the experimental data of Sardarov (1981).

6. Concluding remarks

Although seismogeochemical algorithms are not a new research topic, their guidelines and validation criteria have yet to be defined. As seismogeochemical studies have been fragmentary and unsystematic and the results obtained were often ambiguous and controversial, very few opportunities allowed definite mathematical relations between geochemical and seismic parameters to be formulated.

Currently available algorithms are based on gas-geochemistry. Algorithms based on theoretical physical models do not consider recent studies of gas migration processes (*i.e.*, rapid and long-distance gas movements from the focal zone). Empirical algorithms are often based on a limited number of data and need validation for different geologic environments. Nevertheless empirical algorithms represent a unique tool to predict earthquakes without a full understanding of both rock-mechanics – fluid geochemistry interactions and local and regional stress-field recognition .

The algorithms of Sardarov (1981) and Rikitake (1987) have shown some success for Rn and other geochemical elements. The former suggests that precursor time is independent of seismic data, the latter just uses it to predict the earthquake magnitude. This contrast must be solved for their validation.

Anyway, before formulating or using seismogeochemical algorithms, an interdisciplinary task study, involving different methodological approach (structural geology, fault zone rheology and fluidodynamics, stress-strain field reconstruction, hydrogeology, paleo-seismology, fluid-geochemistry, etc.) in the selected test sites for earthquake prediction studies, is mandatory.

Appendix

A short deeper explanation about the LRFM is needed.

The LRFM would apply to radon and to stable precursors (CO_2, He), for which there are no limits on the source depth. However even for Rn several observations suggest unconventional transport processes inducing rapid upflow. Conventionally, the diffusion modelling of Rn by Soonawala and Telford (1980) suggests that maximum diffusion distances for Rn are of the order of tens of meters. The fluid transport models of Mogro-Campero and Fleischer (1979) suggest distances of hundreds of meters. Detectable radon concentration anomalies from more than 500-700 m deep sources could be explained only if a flow velocity of tens of m/day is assumed for the pore filling medium; flow velocities of this order of magnitude cannot be taken – in general – as realistic ones from geological viewpoint, excluding some extreme cases like highly permeable faults in volcanic or post-volcanic areas. However according to the «geogas» models (see text for references), it seems reasonable that the buoyant force resulting from the density difference between groundwater and gas (*i.e.*, microbubbles) can ensure very high transport velocities. Durrance and Gregory (1990) suggest «rapid movement of carrier gas (and Rn) within groundwater systems» especially in hydrothermal systems (not necessarily linked to volcanism). Durrance and Heath (*Mineralogical Magazine*, **49**, 289-299, 1985) concluded that high concentration of radon in surface

arose from discharge of groundwater on rising limbs of convection cells with dimensions of 5-10 km. Etiope and Lombardi (1996) observed transport rates of He and solid metallic and radioactive microparticles, induced by rising microbubbles in natural coarse sand, of the order of 0.01-0.1 m/s (800-8000 m/day). We think that at least caution is needed to disregard *a priori* the possibility of rapid and long-range gas transport. The LRFM is therefore a real perspective to be considered in earthquake prediction studies.

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