

Spatial selectivity of earthquake's precursors

I.I. Rokityansky *

Institute of geophysics, National Academy of Sciences of Ukraine, POB-70, Kiev-146, 03146, Ukraine

Accepted 6 February 2006

Available online 11 May 2006

Abstract

Multiparameter monitoring of earthquake's (EQ) precursors reveals their selective localization (selectivity), i.e. a precursor can be observable in relatively small selected sensitive area(s) and not observable over remaining vast region. Selectivity and long distance appearance of precursors are rather strange and difficult for explanation, if the Earth is considered as uniform or horizontally layered, but quite natural for the real Earth, which is saturated by inhomogeneities and channels of different scale and nature. Three kinds of channels are proposed for explanation of selectivity: electrically conductive path (for electrical precursors), hydraulic channel and magma intrusion in the stage of emplacement.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Earthquake's precursor; Spatial selectivity; Channeling; Conductivity structure; Magma emplacement

1. Introduction

Posteriori analysis shows that any strong earthquake (EQ) is preceded by a variety of precursors. They are: volatile outcome, level and composition of ground water, variations of electric and magnetic fields, EM-emission, atmosphere luminosity, variations of ionosphere parameters, etc. (Hayakawa and Fujinawa, 1994; Hayakawa, 1999).

In the early 80's P. Varotsos, K. Alexopoulos and K. Nomicos (VAN) discovered in Greece a new EQ precursor which they named seismic electric signal (SES) (Varotsos et al., 1981). Continuous SES observation with 12–18 stations in Greece during 24 years reveals that every SES is followed by moderate or strong EQ. It should be noted that SES appears not everywhere around future EQ, but only in some selected sensitive areas; this property was named selectivity effect. Other types of precursors also exhibit in many cases this feature: selectivity and long distance appearance.

Stress accumulation in the focal zone of impending earthquake is traditionally considered as primary cause of precursory phenomena. Theoretical estimations of a precursor "propagation" in the uniform or horizontally layered (1D) Earth (Bernard, 1992) predict strong monotonous spatial attenuation of the precursor amplitude, and, at the distance (from the source) of the order of few source lengths, precursor should become not observable (below noise level). Such a result contradicts to the observed data, in which spatial change of a precursor is strongly non-monotonous. It leads to a supposition that the real Earth is strongly non-uniform and it contains channels, which allow long distance transport of a precursor and create the selectivity effect. This consideration is valid in the framework of traditional paradigm: the source of a precursor is located in the focal volume of the related EQ. Observational data validate also the extended paradigm: precursory phenomena are formed in an area much larger than the source of the subsequent EQ (Keilis-Borok et al., 1999). This approach opens new possibilities for explanation of precursor properties, and one of them will be used below (magma channel).

At least three kinds of channeling can be proposed for the explanation of the SES selectivity effect: conductive,

* Fax: +38044 450 2520.

E-mail address: rokityansky@yahoo.com

hydraulic and magma channels. We will consider them in the following.

2. Electric conductive channel

For the explanation of the selectivity effect, Varotsos and Alexopoulos (1986) suggested the following model: the earthquake preparation zone lies in the vicinity of a long conductor. When the SES is emitted, the current follows the conductive channel through which most of the current travels. Thus, if the emitting current dipole source lies close to a highly conductive channel and the measuring station lies at a site close to the upper end of this channel, the electric field is appreciably stronger than in the case of a homogeneous or horizontally layered earth. Recently the VAN group published computational results, which yield quantitative estimation of electromagnetic precursor behavior for conductive channels of different configuration (Varotsos et al., 2000a,b). The effect of electric field local enhancement is sufficiently strong to explain observed SES peculiarities. To check the plausibility of this explanation, an independent study of conductive channels should be performed.

Such a study is available by using magnetotelluric sounding (MTS) and especially magnetovariational profiling (MVP) methods. The electrical conductivity anomalies, detected by MVP method, are in many cases conductive channels, i.e. long narrow conductors, composed of mineralized water solutions in fractured zones, or of electroni-

cally conducting minerals, or melt/magma formations. Having before 1990 preferably long period ($T > 10$ s) instruments, MVP method detected large scale (channels hundreds km long) anomalies (Rokityansky, 1982). In the last decade, magnetotelluric instruments allow us to register short period variations ($T > 0.001$ s) and many local scale conductivity anomalies appeared on the records. Unfortunately, this fact does not have yet wide recognition and adequate geological evaluation. One example of conductive channels detection is the detailed MTS-MVP study of the SES sensitive Ioannina area in Greece (Eftaxias et al., 2002).

In MTS-MVP methods, the source of the field is located in the ionosphere. Looking for an analog with SES propagation from focal volume, let us consider the experiment “Khibiny” with strong man made MHD-source (Velikhov, 1989; Rokityansky and Zhamaletdinov, 2004). A current up to 20,000 A was injected via a special electrode system into sea water at two sides of the narrow (7 km) isthmus of peninsula Rybachy at the northern tip of the large Cola Peninsula in the north-western part of Baltic shield (Fig. 1). Current loops in the sea and leakage currents into the lithosphere create electromagnetic fields, which were measured in more than hundred sites at the distance up to 700 km from the source. In the area of investigation, two regional conductivity anomalies were known as outcrops of ore containing minerals with electronic conductivity. The first one, Imandra Varzuga runs to the East, the second one, Pechenga, runs to the West. The latter one was crossed by 4

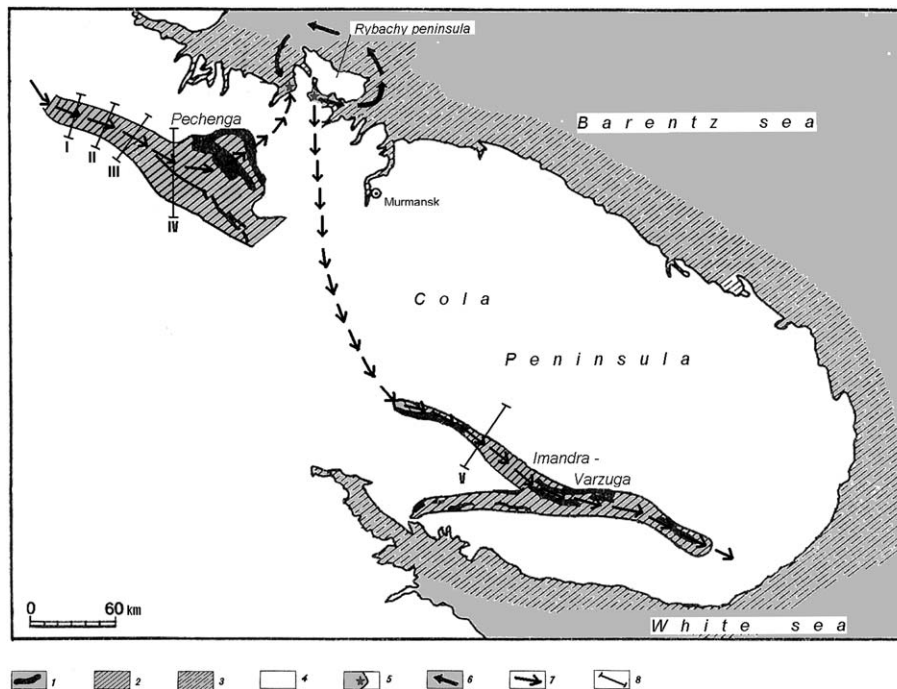


Fig. 1. Channeling of the currents generated by MHD source into conductive zones Pechenga and Imandra-Varzuga in Cola peninsula, north-eastern part of Baltic shield. 1 – outcrops of electronic conductors, 2 – good conducting formations, 3 – sea water, 4 – resistive blocks, 5 – electrodes in sea connected to impulsive MHD source, 6 – currents in sea, 7 – currents channeling in land, 8 – profiles of EM measurements in the western part of Pechenga structure (composed by data (Velikhov, 1989) and (Rokityansky and Zhamaletdinov, 2004)).

profiles of detailed EM observations, located from 80 to 140 km from the source. The current channeled along western continuation of Pechenga structure was calculated from 10–12 measurements of magnetic field at every profile. This current normalized to source current 20,000 A was 60 A at the nearest profile and 40 A at the most remote profile. Outside of the anomaly electromagnetic field diminishes much stronger at comparable distance. Thus, the experiment “Khibiny” shows that quasi-dipole source with moment $E+8 \text{ A m}$ (comparable with the moment expected in focal volume of an earthquake of magnitude 6), separated from the conductive structure by a few dozens of km, can create sufficiently large current in a conductor and travel along it with low attenuation at long distance.

3. Hydraulic channel

Dobrovolsky et al. (1989) explained SES as a local electrokinetic potential created by percolation of the pore fluids driven by excessive pressure arising as result of stress and strain accumulation in rocks in the course of EQ preparation. Bernard (1992) calculated that pre-seismic strain, decaying with distance R from focal volume as R^{-3} in the uniform medium, cannot create observable electrokinetic potential at long distance, but can trigger (at the distances up to 10–20 focal source lengths) transient flow between fluid instabilities and create stream potential in the vicinity of SES sensitive place. This approach can explain the selectivity effect, but not the long distance appearance of a precursor. The author proposes to supplement Bernard’s approach by introduction of a quasi-1D hydraulic path of enhanced fluid permeability, along which excessive pressure can be transmitted from the focal volume to the neighborhood of sensitive site via long distance with small attenuation and time delay.

The existence of the hydraulic channeling is manifested by many direct and indirect observations. The simultaneous (in the limits of a day) changes of water level were observed in Sakhalin Island in wells hundreds of kilometers apart of each other and of related EQ epicenter (Monakhov, 1980). Many examples of spatial selectivity and long distance appearance of different hydrogeological precursors were collected in Japan, China, USA (Roeloffs, 1996, 1998; Tsunogai and Wakita, 1995). The precursory changes of the water level in wells may amount to a good fraction of a meter. It can be enough to trigger stream of the water and create a local seismic electric signal of electrokinetic origin.

Consider two examples from Armenia (Balassanian, 1999). Monitoring of underground water level was performed in 13 sites, but clear seismic related signal was observed only in one, i.e. Azatan (Fig. 2). 7 stations monitored variations of Helium dissolved in underground water, but the seismic related variations were observed only in one station, i.e. Kajaran. This station clearly recorded variations related to four strongest recent earthquakes in the region: Norman, Turkey, 1983, $M = 6.8$; Spitak, Armenia, 1988, $M = 7.1$; Roudbar, Iran, 1990, $M = 7.3$; Racha,

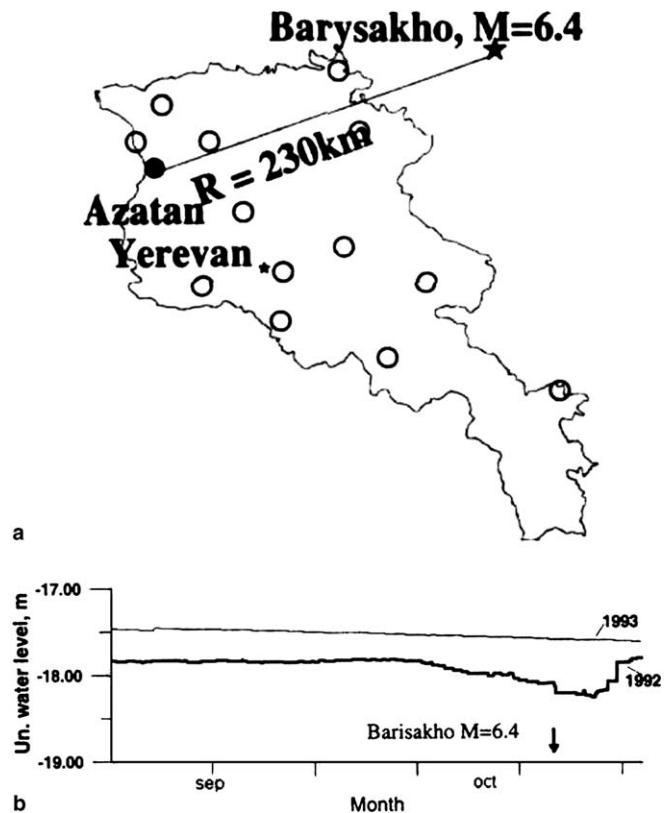


Fig. 2. Underground water level variations (b) at the station Azatan (a) before and after the Barisakho EQ, Georgia, 1992. Open circles are the measurement sites, the filled circle is Azatan station, and the contour marks the borders of Armenia (Balassanian, 1999).

Georgia, 1991, $M = 7.1$. The distance from Kajaran to the EQ epicenters ranged from 250 to 410 km. For the four EQs, Kajaran was the most remote (from epicenters) station, nevertheless nearer stations did not record seismic related changes of Helium content. Selectivity was also observed for other parameters: geomagnetic variations, non-stationary electromagnetic processes.

4. Magma channel (sub-lateral magma emplacement)

The third explanation is based on the suggestion that a lateral magma emplacement along the neutral buoyancy level can be the cause of some crustal earthquakes and their precursors (Guterman and Khazan, 1994, 2003; Rokityansky, 1999, 2002). For volcanic environment, such a cause is well known: volcanic earthquakes manifest magma movement and they are used for prediction of volcanic eruptions. Usually, shallow volcanic EQs are not very strong, because excessive pressure can be released by an eruption or Earth’s surface inflation. But if the rocks surrounding magma intrusion are sufficiently rigid and deep seated, large scale stress accumulation can occur which can result in a stronger earthquake. The examples are four EQs with magnitude M larger than 6 in Long Valley caldera, California, in May 1984 (Miller et al., 1998) and five EQs with $M > 6$ during the Miyake-Kozu swarm event in June–August 2000 near Japan coast (Japan Meteorological

Agency, 2000; Sakai et al., 2001). The last event was studied in details by land (at islands) and sea bottom seismometer observations, and GPS ground motion measurements. Consider this event. On June 26 a large seismic swarm started under Miyake-jima volcano (Fig. 3) and then it rapidly migrated in northwest direction, reaching in 5 days, the area near Kozu-shima island about 30 km away, and resulted on July 1 in a strong EQ of magnitude $M = 6.4$. Using the data of Fig. 3 and results of seismic data inversion (Sakai et al., 2001), the model of magma emplacement for the interval June 26–July 1 was composed (Fig. 4). The mean velocity of the swarm migration was equal 0.15 m/s, but it was strongly non-uniform, i.e. with stops, back motion and jumps (which can be interpreted by new magma portions entering). The last jump resulted in the strong EQ of July 1, 2000.

In the region of the swarm, there was electric potential monitoring on Niijima island (20 km to the North from the epicenter of EQ on July 1) with 6 long (1–6 km) dipoles. Two months prior to the swarm of earthquakes, one (only one of 6 – once more selectivity!) of dipoles started continuous record of impulses and oscillations with period of one to a few minutes, which lasted 4 months up to swarm terminal (Uyeda et al., 2002).

It is a widely accepted opinion that the EQs of magmatic origin are created as results of tensile and volumetric isotropic stress accumulation (Julian et al., 1998), which is rather slow and should not result in strong EQ. The recent results of numerical and laboratory physical modeling of fluid driven crack propagation (Guterman and Khazan, 2003) open new possibilities for the explanation of the strong EQs of magmatic origin. The modeling shows that

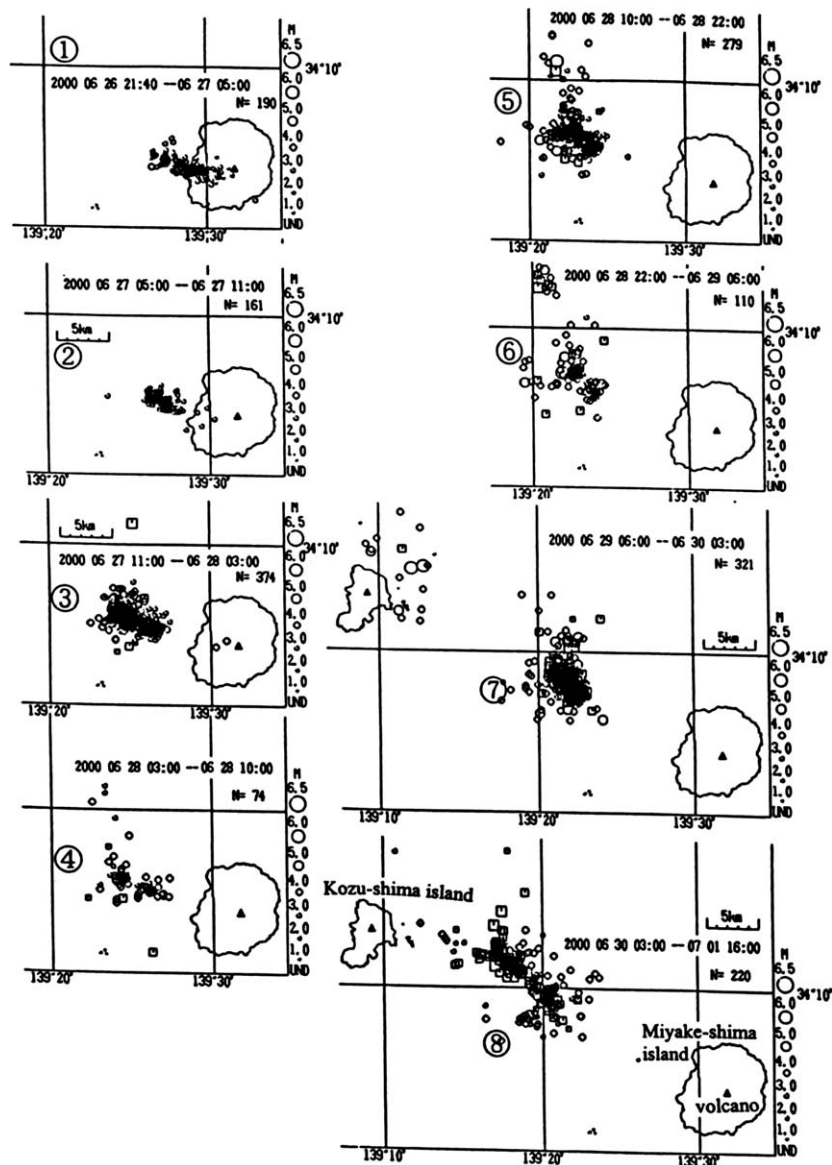


Fig. 3. Distribution of epicenters of Miyake-Kozu EQ swarm event for 8 consecutive time intervals from June 26 till July 1, 2000. The star denotes EQ of $M = 6.4$ occurred on June 1, 2000 (Japan Meteorological Agency, 2000).

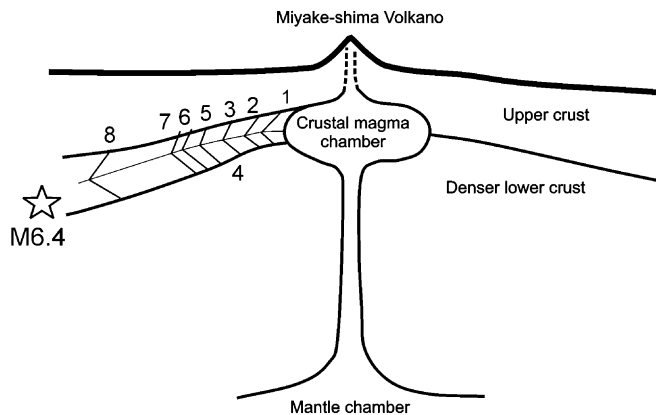


Fig. 4. Model of lateral magma emplacement along neutral buoyancy level consistent with June 26–July 1, 2000, Miyake-Kozu swarm development resulting in the EQ of $M = 6.4$, shown by star. Numbers along magma path correspond to consecutive time intervals in Fig. 3.

if the fluid pressure is not very high (slightly exceeds the lithostatic one), cracks propagate quasi-stationary as tensile ones. If the fluid pressure strongly exceeds (even for a short time as result of fluctuations) the lithostatic pressure, then under favorable geometry (ratio of crack width to its depths not strongly different from 1), both tensile and shear strengths of embedding rocks can be exceeded. It can result in the shear crack formation (i.e. in EQ) at the tip of magma emplacement plane, normal to it.

Terrestrial data of intrusive geology and modern volcanology as well as satellite survey on Venus, reveal abundance of dikes, sills, magma fields, i.e. ancient and recent lateral magma emplacements with lengths up to 2000 km. It means that magma emplacement can begin in an active region (mantle plume, volcanic edifice) and continue into a platform as it was the case for Proterozoic giant radiating dike swarms traversing the shields (Ernst et al., 1995). Recent and coeval dike swarm formation also occurs and have been observed in volcanic areas. Gudmundsson et al. (1999) studied 5000 dykes of late Tertiary to Holocene age in Iceland and Tenerife and found that most dykes become arrested at various crustal levels and never reach the Earth's surface. It gives a ground to suppose that if a (partially) melted zone does exist somewhere in the crust (as result of modern tectonic activation, for example, or ancient reminder), it can generate sub-lateral magma emplacements and related EQs without surface volcanism manifestation.

Dissipation of energy from hot magma into cold embedding rocks put limitation on the duration of magma emplacement process. Typically, it lasts from a few days to several weeks, as theoretical estimations show (Ernst et al., 1995; Rubin, 1995; Fialko and Rubin, 1998). If the geological environment along magma emplacement path is favorable for a stress accumulation in some place, the final stage of earthquake preparation process can start and it can be very fast. In this case, precursors can be the most intensive in the beginning or somewhere along the

path, far away from future focal zone and many days before EQ.

5. Conclusion

Each of the three channeling models outlined above can explain the remote selective sensitivity of observed precursors. They can also act together in a variety of combinations dependent on geological environment.

The idea of sub-lateral channels in the Earth's interior may be not a new one, but it is not well known and commonly accepted. Therefore, in some works, the selectivity of a precursor is considered as not corresponding to the theory (of signal "propagation" in uniform and horizontally layered Earth) and used as an argument against the recognition of corresponding phenomenon (SES, for example) as a precursor of an EQ (Wiss, 1996; Geller, 1997).

References

- Balassanian, S.Y., 1999. The anomalous daily dynamics of local geophysical and geochemical fields (ADF) effect study in the connection with earthquake preparation and occurrence. *Phys. Chem. Earth (A)* 24, 741–752.
- Bernard, P., 1992. Plausibility of long distance electrotelluric precursors to earthquake. *J. Geophys. Res.* 97, 17531–17546.
- Dobrovolsky, I.P., Gershenson, N.I., Gokhberg, M.B., 1989. Theory of electrokinetic effects occurring at the final stage in the preparation of a tectonic earthquake. *Phys. Earth Planet. Interiors* 57, 144–156.
- Eftaxias, K., Rokityansky, I.I., Bogris, N., Balasis, G., Varotsos, P., 2002. Magnetovariational and Magnetotelluric study of Ioannina region sensitive to Seismic Electric Signals (SES). *J. Atmos. Electricity* 22, 113–137.
- Ernst, R.E., Head, J.W., Parfitt, E., Grosfils, E., Wilson, L., 1995. Giant radiating dyke swarms on Earth and Venus. *Earth-Sci. Rev.* 39, 1–58.
- Fialko, Y.A., Rubin, A.M., 1998. Thermodynamics of lateral dyke propagation: Implications for crustal accretion at slow-spreading mid-ocean ridges. *J. Geophys. Res.* 103, 2501–2514.
- Geller, R.J., 1997. Earthquake prediction: A critical review. *Geophys. J. Int.* 131, 425–450.
- Gudmundsson, A., Marinoni, L.B., Marty, J., 1999. Injection and arrest of dykes: implication for volcanic hazards. *J. Volcanol. Geotherm. Res.* 88, 11–13.
- Guterman, V.G., Khazan, Y.M., 1994. A possible mechanism of strong shallow earthquake preparation. *Geophys. J.* 16 (1), 22–29, in Russian.
- Guterman, V.G., Khazan, Y.M., 2003. Can a crack of hydro/magma-fracture create a shear crack? *Geophys. J.* 25 (1), 55–71, in Russian.
- Hayakawa, M. (Ed.), 1999. Atmospheric and Ionospheric Electromagnetic Phenomena Associated With Earthquakes. *Terra Sci. Publ. Comp.*, Tokyo, p. 996.
- Hayakawa, M., Fujinawa, Y. (Eds.), 1994. Electromagnetic Phenomena Related to Earthquake Prediction. *Terra Sci. Publ. Comp.*, Tokyo, p. 677.
- Japan Meteorological Agency, 2000. Recent seismic activity in the Miyakejima and Nijima-Kozushima region, Japan – the largest earthquake swarm ever recorded. *Earth Planets Space* 52 (8), i–viii.
- Julian, B.R., Miller, A.D., Foulger, G.R., 1998. Non-double-couple earthquakes. 1. Theory. *Rev. Geophys.* 36, 525–549.
- Keilis-Borok, V., Kossobokov, V., Rotwain, I., Soloviev, A., 1999. Earthquake prediction: recent results and what comes next. Abstracts of IUGG99 vol. A, 19–31 July 1999, Birmingham, p. 137.
- Miller, A.D., Foulger, G.R., Julian, B.R., 1998. Non-double-couple earthquakes. 2. Observations. *Rev. Geophys.* 36, 551–568.

- Monakhov, F.I., 1980. Formation mechanism of the hydrogeodynamic precursor. *Dokl. Akad. Nauk SSSR* 251 (4), 828–831, in Russian.
- Roeloffs, E., 1996. Poroelastic techniques in the study of earthquake-related hydrologic phenomena. *Adv. Geophys.* 37, 135–195.
- Roeloffs, E., 1998. Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes. *J. Geophys. Res.* 103 (B1), 869–889.
- Rokityansky, I.I., 1982. *Geoelectromagnetic investigation of the Earth's crust and mantle*. Springer Verlag, Berlin, Heidelberg, New York, p. 381.
- Rokityansky, I.I., 1999. Anomalous phenomena preceding earthquakes. *Phys. Chem. Earth (A)* 24, 731–734.
- Rokityansky, I.I., 2002. On the physical nature of remote precursors. *J. Atmospheric Electricity* 22, 165–182.
- Rokityansky, I.I., Zhamaletdinov, A.A., 2004. Conductive channels in the Earth crust. Abstract 286-16 at 32nd International Geological Congress, August 20–28, 2004, Florence, Italy.
- Rubin, A.M., 1995. Propagation of magma filled cracks. *Annu. Rev. Earth Planet. Sci.* 23, 287–336.
- Sakai, S., Yamada, T., Ide, S., Mochizuki, M., Shiobara, H., Urabe, T., Hirata, N., Shinohara, M., Kanazawa, T., Nishizawa, A., Fujie, G., Mikada, H., 2001. Magma migration from the point of view of seismic activity in the volcanism of Miyake-jima island in 2000. *J. of Geography* 110 (2), 145–155 (in Japanese).
- Tsunogai, U., Wakita, H., 1995. Precursory chemical changes in ground water: Kobe earthquake, Japan. *Science* 269, 61–63.
- Uyeda, S., Hayakawa, M., Nagao, T., Molchanov, O., Hattori, K., Orihara, Y., Gotoh, K., Akinaga, Y., Tanaka, H., 2002. Electric and magnetic phenomena observed before the volcano-seismic activity 2000 in the Izu Island region, Japan. *Proc. US Nat. Acad. Sci.* 99, 7352–7355.
- Varotsos, P., Alexopoulos, K., 1986. Stimulated current emission in the Earth. In: Amelinckx, S., Gevers, R., Nihoul, J. (Eds.), *Thermodynamics of Point Defects and Their Relation With Bulk Properties*. North Holland, Amsterdam, pp. 136–142.
- Varotsos, P., Alexopoulos, K., Nomicos, K., 1981. Seismic electric currents. *Prakt. Akad. Athenon* 56, 277–286.
- Varotsos, P., Sarlis, N., Lazaridou, M., 2000a. Transmission of stress induced electric signals in dielectric media. Part 2. *Acta Geophys. Polonica* 48, 141–177.
- Varotsos, P., Sarlis, N., Skordas, E., 2000b. Transmission of stress induced electric signals in dielectric media. Part 3. *Acta Geophys. Polonica* 48, 263–297.
- Velikhov, E.P., Chief Editor 1989. *Geoelectric investigations with powerful source in the Baltic shield*. Nauka, Moscow, p. 272 (in Russian).
- Wiss, M., 1996. Brief summary of some reasons why the VAN hypothesis for predicting earthquakes has to be rejected. In: Lighthill, J. (Ed.), *Critical Review of VAN*. World Sci. Publ., Singapore, pp. 250–264.