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HYDROGEOSEISMOLOGICAL METHODS AND EARTHQUAKE PREDICTION

***Komatina-Petrović S.*[1], *Komatina M.*[2], *Radović V.*[3], *Dimiskovska B.*[4]**

ГИДРОГЕОСЕЙСМОЛОГИЧЕСКИЕ МЕТОДЫ И ПРОГНОЗИРОВАНИЕ ЗЕМЛЕТРЯСЕНИЙ

Коматина-Петрович С., Коматина М., Радович В., Димисковска Б.

Прогнозирование землетрясений — очень деликатная задача, которая, в основном, не решена до сих пор. Из практики очевидно, что возможности гидрогеосейсмологии для разработки подходящих методов и выявления индикаторов — предвестников землетрясений являются значительными. В данной статье представлен обзор гидрогеосейсмологических методов, используемых по всему миру, а также применяемых гидрогеохимических и гидродинамических индикаторов. Результаты исследований на территории Сербии также представлены в статье.

Ключевые слова: землетрясения, гидрогеосейсмологические методы, прогнозирование землетрясений, Сербия.

From the ancient times, demolishing earthquakes attract geoscientists' attention. In the world literature, contributions related to changes occurred during and after earthquakes – water temperature and level in boreholes and springs, geyser activities, springs mixing and disappearing, sudden deposition, are presented [1]. In 1966, systematic weekly regime observations of gas chemical and isotopic groundwater content of Pritashkent artesian basin were organized, in order to define changes, in other words – earthquake precursors. Similar observations were performed in all seismoactive zones of the former USSR, but also in other countries. Special topic of attention is sectors along large seismological faults, as deep Gissaro-koksaaljski fault in Tadzhikistan or San Andreas fault area in California (USA). Number of polygons grows, and content of radon or helium is measured, but also changes in yield, chemical content and water temperature are monitored [2].

Explorations lasting several years at the territory of northern Caucasus made successful predictions of Dagestan earthquakes in 1974–1976 possible [3]. It was determined that each water point has its own range of informative components for exploration of hydrogeochemical indicators of earthquakes. Among the best indicators, macro components are included, with universal hydrogeochemical indicator – chlorine content in groundwater. With changes of physico-chemical indicators of groundwater, geodynamic effects simultaneously appeared (sudden changes in yield of boreholes or springs, even several hundred kilometers from the focus).

Special attention is directed to analysis of hydrodynamic regime. At numerous sectors of the former USSR, daily registration of piezometric pressure, groundwater level and other hydrogeodynamical parameters is carried out. Results obtained by monitoring periodic changes of geysers in Iceland and Yellowstone national park (USA) before the earthquake are of special attention.

Hydrogeoseismological exploration in order to predict earthquake in USA started in

[1]Komatina-Petrović Snežana, Professor, Doctor of Sciences, President of Association of Geophysicists and Environmentalists of Serbia; e-mail: unabojan@eunet.rs.

[2]Komatina Miomir, Doctor of Sciences, Association of Geophysicists and Environmentalists of Serbia; e-mail: unabojan@eunet.rs.

[3]Radović Vesela, Doctor of Sciences, Assistant Professor at Faculty of Environmental Science, Educons University; e-mail: vesela.radovic@educons.edu.rs.

[4]Dimiskovska Biserka, Doctor of Sciences, Assistant Professor at Institute of Earthquake Engineering and Engineering Seismology University; e-mail: biserka@pluto.iziis.ukim.edu.mk.

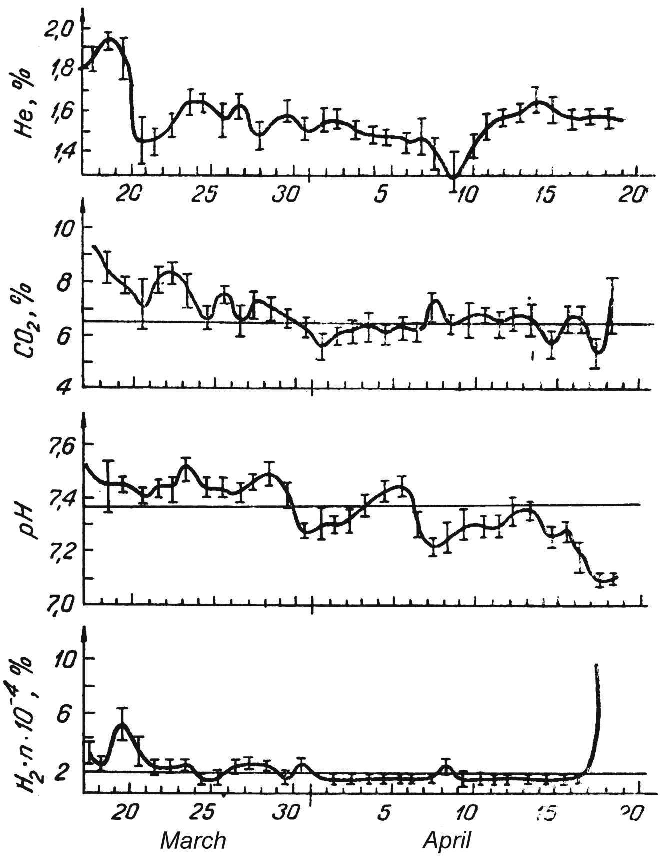

Figure 1. Changes in gas concentration before the earthquake in 1976 [10]

1974 [4]. Radon contents in air and soil [4]], as well as changes in groundwater level within the San Andreas fault area [5], were measured.

At the same time, hydrogeoseismological exploration started in Japan [6, 7]. The most important result is some characteristic of raising groundwater level before and after the earthquake.

Several years later, the same kind of exploration started to develop in Italy, Yugoslavia [8] Austria, France, Bulgaria and other countries. Generally speaking, some results were obtained and perspectives of methods based on hydrodynamic regime monitoring, chemical, gas and isotope content of groundwater in relation with seismic activity within appropriate geotectonic conditions verified.

1. Review of hydrogeochemical and hydrogeochemical precursors of earthquakes

Hydrogeoseismological precursors (indicators) of the earthquakes are based mainly on results of Tashkent polygon, which is well organized, with deep artesian horizons [9].

Hydrogeochemical anomalies for the polygon are controlled by wide range of elements – indicators, including carbon, nitrogen, hydrogen, chemically neutral radiogenic gas (helium, argon, radioactive uranium, radon), isotope relations U236/U238, C13/C12, Ar40/Ar36, as well as macro- and microelements: fluoride, boron, chlorine, Eh and Ph quantities, mineralization, etc. Mentioned indicators proceed to tectonic earthquakes, excluding radioactive elements (uranium and appropriate isotopes), content of macro components and groundwater mineralization. Their reliability depends on the intensity of coming event, geological-tectonic structure, seismicity and frequency, presence of seismological faults, mechanism of the future focus and distance to the monitoring point. That is why the same (universal) model of earthquake prediction could not be expected [10].

On the basis of monitoring related to variations in helium- and CO_2- content in 4-hours

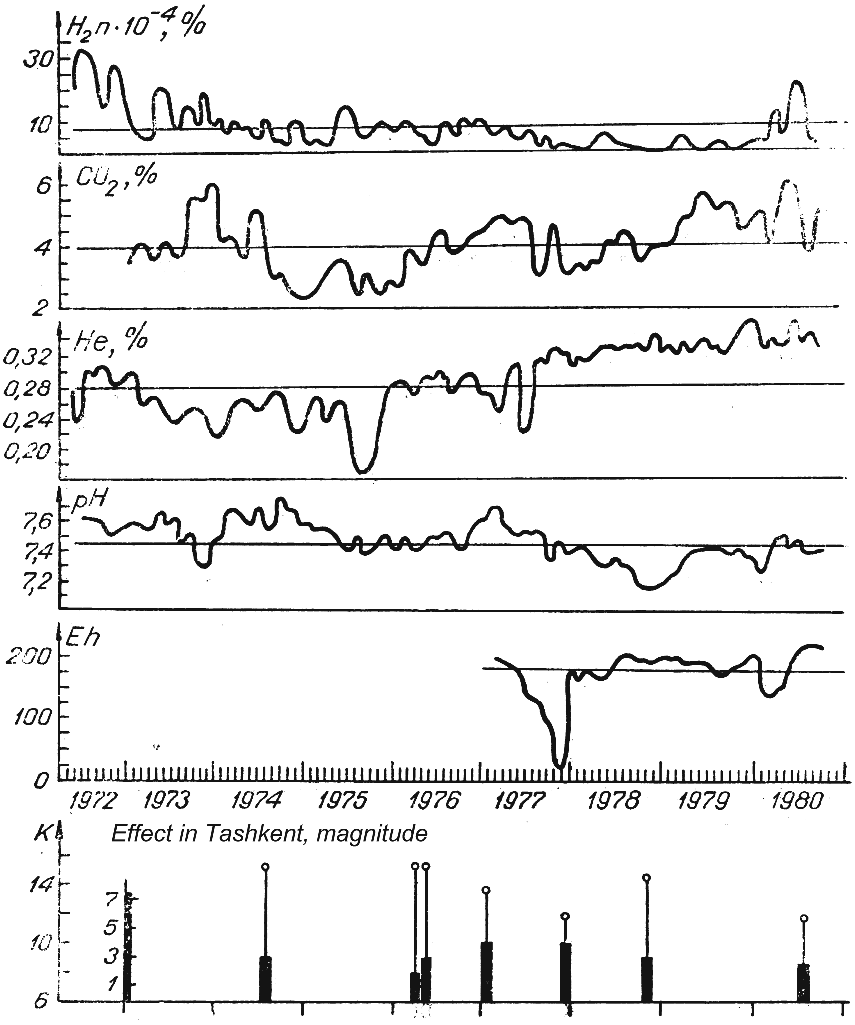

Figure 2. Changes in groundwater chemical content or the Tashkent geodynamic polygon for the 1972–1980 period [9]

intervals for one observed borehole, noticeable changes a day before the Gaslian earthquake (April 8, 1976) could be distinguished (Fig. 1). At the end of March, helium content decreased suddenly, with minimum value registered two days before the main event. Similar situation was defined before the strong earthquakes at the beginning and the end of 1977 and in November, 1978. Also, pH values decreased to the minimum just before the event (Fig. 2). Extreme values of short-period anomalies related to gas (including radon) content and microcomponents were the indicator to predict strong earthquake. However, data on variations in chemical content of gas were recorded for only one polygon and that is why focus of the coming event was not possible to be determined [9].

In 1979, at the Tashkent geodynamic polygon, no characteristic anomalies were defined, excluding very high CO_2 content at one of the observed boreholes. At the beginning of 1980, significant changes in numerous parameters were recorded, directing to the conclusion that period of intensive seismic activity is beginning (Fig. 3). In the middle of July 1980, earthquake in the Fergan valley happened, 165 km far from the monitoring points (in Tashkent, it was event of 4–5 degrees). It is interesting to note significant 6-months decrease of chlorine content, starting from May, 1980.

According to results of investigations referring to several strong earthquakes, radon content changes a lot. After the main shock (probably before it, too), radon content at the areas of foci is predominantly increased, decreasing gradually, with extreme variations during the foreshocks. At some localities, correlation be-

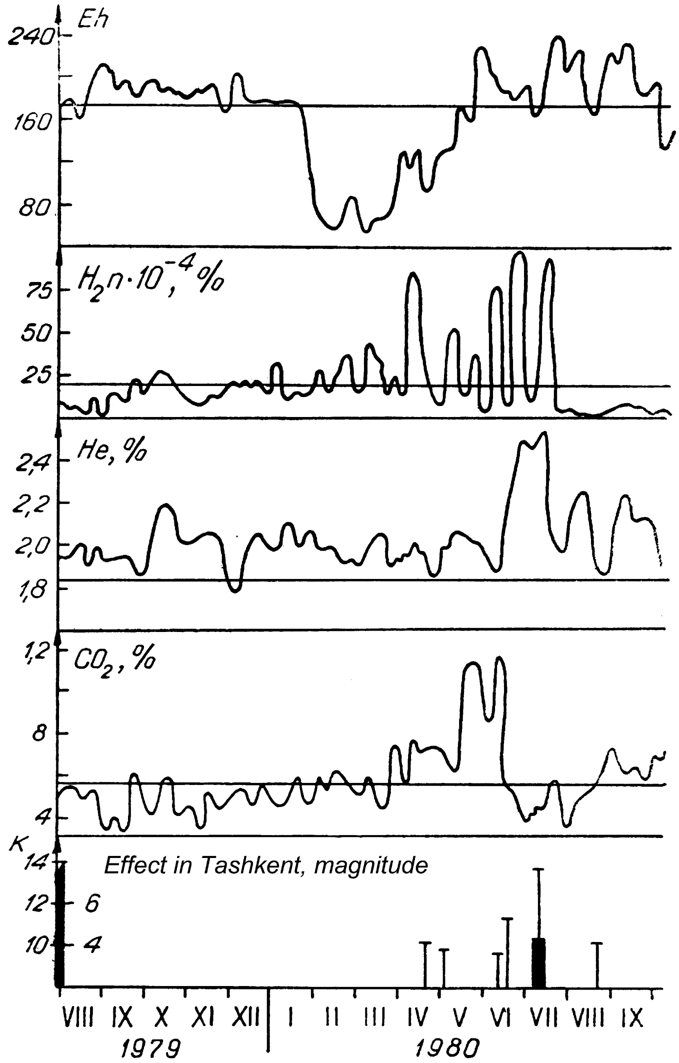

Figure 3. Changes in groundwater chemical content after the Alai earthquake in 1978 [9]

tween radon content and hydrodynamic indicators is distinguished: when piezometric pressure decreases, radon content increases and vice versa. Besides, during the strong events, it is important to analyze variations in the Earth's electromagnetic field, particularly EM precursors of the earthquakes.

Isotopic characteristics of carbon and argon are known as useful indicators of tectonic movements. Among all, increase in Ar40 content during the period of seismic activity is noticeable, as well as decrease during the period of inactivity. Also, interesting results were obtained by measuring isotope relationships of Ar40/Ar36, Ar36/Ar38, He4/Ar40 and C13/C12.

Hydrogeodynamical anomalies and hydrodynamic effects marking earthquakes are intensively studied during the past four decades. Among all, it was determined that hydrogeodynamical parameters of groundwater are closely connected to seismic occurrences [10]. So, system piezometric pressure – deformations is included in sensitive indicators of tension state of rock masses, and hydrodynamic effects – into carriers of geo-chemical anomalies (radon, etc.). That is why in earthquake prediction not only hydrodynamic, but also hydrogeochemical methods are used. Note that piezometric pressure and gradient increase if water-bearing horizon is submitted to compression forces, and decrease during opening the Earth's crust.

As an example for hydrogeodynamical anomalies investigation, Tashkent polygon is interesting. During the period 1976–1980, several strong earthquakes were registered. So, appropriate hydrodynamic anomalies originated. During the Alai earthquake (Novem-

Figure 4. Artesian well BN-1/88 [12]

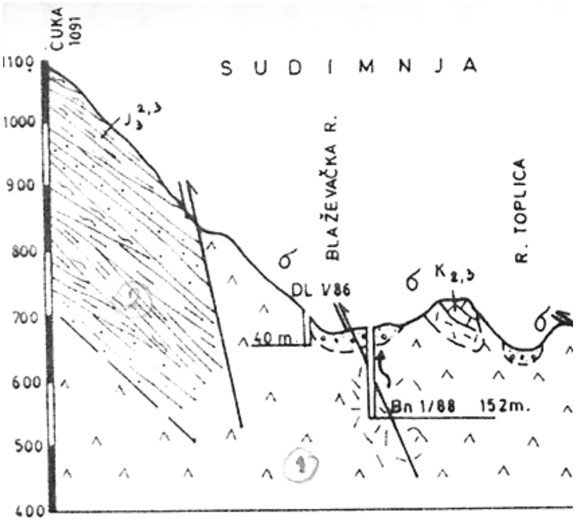

Figure 5. Geological cross-section at Sudimlje locality. 1. ultramaphites. 2. Upper Jurassic sediments [13]

Period of monitoring	Yield (l/s)
Sept. - Dec., 1988	3.0 l/s
Dec.,1988 – April, 1989	2.5 l/s
April – July, 1989	2.2 l/s
July, 1989 – August, 1990	2.0 l/s
August, 1990 – April, 1991	1.66 l/s

ber 2, 1978 – M7), numerous hydrogeochemical anomalies were distinguished, followed by groundwater hydrodynamic characteristics. Before the event (in October), piezometric pressure was increasing gradually, with sudden increase just a day before the main events. Further, changes in groundwater level before and after the quake were recorded in Japan and other countries.

In Serbia, the first experiments related to the earthquake prediction started at Sudimlje (Kopaonik mt.), in 1985 [12]. Central monitoring point was deep well with thermomineral water. Numerous hydrogeochemical and hydrodynamic indicators were observed. However, the four-year period of monitoring, performed after strong earthquakes in 1980 and 1984, was period without seismic activity. That is reason why significant results were not obtained.

2. Application of hydrogeoseismological method at Kopaonik mt. area

After the disastrous earthquake at Rudnik mt. in 1927, the event happened at Kopaonik mt. is the strongest one in Serbia. This area was known as the 7$^{\text{th}}$ degree category until May 18, 1980, when the earthquake of eight degree (M = 6.0) occurred. Events of the similar intensity repeated in 1984, 1985 and 1986 (I = 60, M = 4.0).

The first experiments related to application of hydrogeoseismological method were performed at the area with the highest seismic intensity – close to Sudimlje village, about 6 km to the NE from Blaževo. It was discovered that spring of mineral water was much stronger after several subsequent earthquakes in September, 1985. Detailed hydrogeological investigations started in 1986, and 132 m deep exploratory-exploitation well was made two years later (Fig. 4). Results of the exploration are presented at *the Project of hydrogeological monitoring station for earthquake prediction in Kopaonik seismic area* [12].

Central monitoring structure was the mentioned well with termomineral water. Numerous hydrogeochemical and hydrodynamic indicators were observed, but data of previous investigations were also useful. Among all, during 1990, twelve complete chemical analyses of water from the well were made, as well as measuring gas content and radioactivity. Monitoring of the artesian well and piezometric pressure started two years before, lasting till the end of 1944. Note that the well cuts intensive fault zone, which is main groundwater conductor to the terrain surface (Fig. 5).

It can be concluded that one of the important earthquake precursors could be sudden change in yield values, in other words – in piezometric pressure. However, period of realization of the Project was during seismic inactivity and it is not possible to justify that assumption [13].

According to complete chemical analyses, content of different macro- and micro components has not changed in such extent (in mg/l):

Na – 193–213
Ca – 100–105
Mg – 86–99
K – 13–14
Li – 0.45–0.50
Sr – 3.28–5.00

Total water mineralization varied between 1.288 and 1.461 mg/l, and significant changes of CO_2 were interesting from the viewpoint of the earthquake prediction. Furthermore, changes in radioactive gas — radon, were also interesting — during the period of observation, radon content was between 9.6 and 0.3 Bq/l.

Changes in piezometric pressure, that is – artesian aquifer capacity is noticeable. Namely, that value is more important during seismic activity in comparison to the period of inactivity:

Note that water temperature was changing in the range of 19°C (during period of seismic activity) and 21° C (during period of inactivity).

There were no seismological conditions for precise evaluation of the mentioned potential indicators and that is why monitoring station stopped to work in 1994. But, proposal of the new project related to continuation of the monitoring activities has been submitted for financing and much complex exploration is expected to be carried out in the coming years [14].

Conclusion

According to the long-term monitoring of variations of various hydrogeological and hydrogeochemical parameters in groundwater of seismoactive areas, it was possible to conclude that, during periods of tectonic activity of the Earth's crust, present geodynamical, hydrogeochemical and other ways of natural equilibrium within geological structures are disturbed, followed by occurrence of anomalies. According to G.A. Mavljanov et al. (1983), in order to solve the problem and find safe complex of hydrogeoseismological precursors, first of all, scientifically based approach in choice of polygons and study areas is required, as well as to unification of methods for measuring and analysis of studied parameters, working out and improving of monitoring and analytical systems, producing automatic systems in order to acquire operation information related to changes of parameters in time [15].

It is impossible to judge place and intensity of potential event on the basis of monitoring data within a study area without existent basic monitoring network system. Hence, it is necessary to use specialized hydrogeoseismological survey at all terrains under the risk.

As hydrogeoseismological exploration is based on systematic regime observations, task of the further development of methods of data statistic processing regarding earthquake precursors is unavoidable. Various correlations among basic quantities of studied anomalies and data referred to the earthquakes are determined in the practice.

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Association of Geophysicists and Environmentalists of Serbia, Beograd, Serbia
Educons University, Sremska Kamenica, Serbia
Institute of Earthquake Engineering and Engineering Seismology University, “Ss. Cyril and Methodius”, Skopje, FYR Macedonia