ISSN 0742-0463, Journal of Volcanology and Seismology, 2015, Vol. 9, No. 5, pp. 326–332. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © P.P. Firstov, E.O. Makarov, A.P. Maksimov, I.I. Chernev, 2015, published in Vulkanologiya i Seismologiya, 2015, No. 5, pp. 43–49.

The Geodynamic Setting in the Northwest Circumference of the Pacific Ocean: Effects on the Dynamics of Subsurface Radon and on the Gas Composition of the Heat Carrier at the Mutnovskii Geoelectric Power Station

P. P. Firstov[a], E. O. Makarov[a], A. P. Maksimov[b], and I. I. Chernev[c]

[a] *Kamchatka Branch, Geophysical Service, Russian Academy of Sciences,*
bul'var Piipa 9, Petropavlovsk-Kamchatskii, 683006 Russia
e-mail: firstov@emsd.ru

[b] *Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences,*
bul'var Piipa 9, Petropavlovsk-Kamchatskii, 683006 Russia
e-mail: maximov@kscnet.ru

[c] *GEOTERM Ltd., Akademika Koroleva 60, Petropavlovsk-Kamchatskii, 683980 Russia*
e-mail: ChernevII@geotherm.rushydro.ru

Received March 10, 2015

Abstract—This paper provides information on the behavior of the radon activity time series for the period from 2000 through 2015 in the water-saturated zone of the Paratunka Geothermal Field and that of the time series that recorded the volumetric fraction of molecular hydrogen in the gaseous heat carrier at well 016 in the Mutnovskii Field, as well as their relationships with the seismicity in the northwestern circumference of the Pacific Ocean. It was concluded that long-term trends in radon activity and the high volumetric fraction of molecular hydrogen in 2014 are caused by a change in the stress field that acts in the subduction zone of the northwest flank of the Pacific Ocean. It is hypothesized that an $M > 7.5$ earthquake is likely to occur during the next 1.5 years. In the opinion of Academician S.A. Fedotov, the most likely location for such an event is between the Shipunskii Peninsula and Shiashkotan Island, Middle Kuril islands.

DOI: 10.1134/S0742046315050048

INTRODUCTION

Degassing processes in the Earth do not occur uniformly either in space or in time; they are largely controlled by the distribution and magnitude of stresses in crustal fault zones of varying hierarchical ranks. Gas migration in the upper crust is governed by diffusion and the filtration properties of rocks, which depend on rock permeability, porosity, and the degree of cracking. At the same time, the filtration properties of the geological medium and the release of radioactive gases from rocks are affected by stress variations (Rudakov, 1992). For this reason changes in the stress and strain of the geological medium during the terminal phase in the precursory processes of large earthquakes must leave their impression on the dynamics of subsurface gases (Rudakov, 1992; Voitov, 2002). The easiest method in geochemical research that can be applied to earthquake prediction is recording radon (^{222}Rn) in subsurface air. That fact that the seismic emanation method has promise for the monitoring of geodynamic processes, in particular, for prediction of earthquakes and rock bursts, has been conclusively proven by many investigators (Avdualiev et al., 1986; Rudakov, 1992; Utkin and Yurkov, 1997; Firstov and Rudakov, 2003; Spivak et al., 2008; Firstov et al., 2007, 2011; Makarov et al., 2012; Steinitz et al., 2003).

We know that the Earth has been releasing flows of a water–gas fluid during its entire geological history without interruption. These flows changed appreciably over time and are not uniform over the Earth, thus bearing the signature of its geodynamic regime and its blocky structure (Letnikov, 2000). In the last decade unequivocal evidence has been obtained that points to a considerable role of hydrogen in earth structure and in the interaction among the geospheres (Larin, 2005; Syvorotkin, 2002). Observations of variation in the concentration of molecular hydrogen (H_2) in a number of geostructural zones worldwide show that such observations have promise for dealing with various geodynamics problems. For example, two $M > 6$ earthquakes occurred in 1998–2000 near observation sites in Dagestan. At 5 months and 2.5 months before these events a steadily increasing concentration of H_2 was recorded, reaching 300% in relative terms (Voitov, 2002).

One distinctive feature in the behavior of H_2 compared with the other gases is its high mobility, especially at higher temperatures. Studies in the dynamics of molecular hydrogen in subsurface gas at the Paratunka Geothermal Field showed impulsive spikes of high intensity that were recorded upon the background of a slowly varying concentration of subsurface H_2 during the 1999–2003 period, with these spikes coinciding with seismicity increases in the Kuril–Kamchatka region (Firstov and Shirokov, 2005).

Gufel'd and Novoselov (2014) showed that a considerable, while not to say the leading, role in continual variations of different sizes in geological medium parameters between the ground surface and the Moho interface is played by interaction between ascending H_2 flows and the solid phase. These processes affect the geological medium in interblock zones, as well as the 3D stresses that are related to pre-fracture processes. Hydrogen degassing affects discontinuous intrablock and interblock structures and plate boundaries, thus controlling their superplastic movements relative to each other (Gufel'd and Novoselov, 2014).

Firstov (2014) pointed out that a long-term precursor of a large earthquake was observed in the subsurface radon (Rn) field. The present study considers the subsequent evolution of the observed trend in subsurface Rn and the behavior of the volume fraction of H_2 in the gas composition of the heat carrier at well 016 in the Mutnovskii Thermal Field as corroborating disturbances in the fluid regime beneath the Kamchatka Peninsula, which thus indicate intensive geodynamic processes in the lithosphere.

BRIEF INFORMATION ON INSTRUMENTATION AND OBSERVATIONAL METHODS

A network of recording stations for Rn observation of the subsurface air in unconsolidated deposits has been operated without interruption during the search for earthquake precursors in the Petropavlovsk-Kamchatskii Geodynamic Test Site since October 1997 (Firstov, 1998). At present, the sensors at all sites are gas-discharge counters of the SBM-19 type that enable passive recording of the Rn concentration as reflected in the β radiation of its short-lived daughter decay products (Firstov and Rudakov, 2003). The monitoring sites are equipped with automated instrument sets for recording the concentration of soil gas (RCSG) based on ALMEMO production-run recorders and additional devices that were developed by Makarov et al. (2012). The sets allow the simultaneous recording of the number of pulses from the SBM-19 counters and other parameters (the concentration of H_2, CO_2, and meteorological quantities). The conversion from concentration to the activity of Rn (A Rn) is performed via the empirical relation A Rn (Bq/m^3) = 9 · N (pulses per minute).

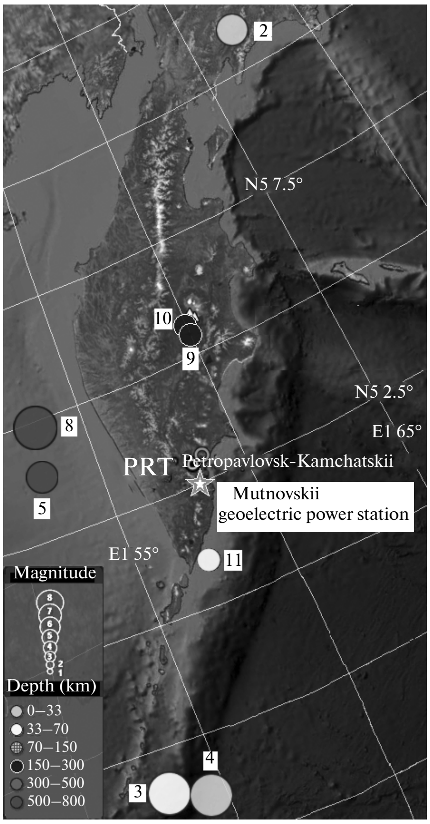

Fig. 1. A map that shows the epicenters of large earthquakes along the northwest circumference of the Pacific Ocean for the last 15 years, and recording stations.

The stations were installed in different structural features along the coast of the Avacha Bay. In addition, each station has its own structure of the eluvial–deluvial deposits in the zone of aeration where the gas-discharge counters are installed; this determines the individual transfer function for changes in stress and strain as reflected in A Rn (strain sensitivity). A detailed description of the instrumentation and recording stations can be found in (Makarov et al., 2012; Firstov et al., 2015).

This paper is concerned with the behavior of the A Rn time series as recorded at the Paratunka station (PRT) during the 2000–2015 period, for a sensor installed at a depth of 3.5 m from the ground surface in the water-saturated zone (WSZ) and of a time series of the volume fraction of H_2 in the gas of the heat carrier at well 016 in the Mutnovskii Field (Fig. 1). The PRT is situated in the river terrace of Korkin Brook, which runs along a nearly east–west fault within the Paratunka graben to which the geothermal system is confined. Thermal water is discharged with concentrations of dissolved Rn ~ 1.5 kBq/m^3 at a distance of 700 m from the PRT down the stream.

Monthly monitoring for the composition of gases in the heat carrier at the wells in the Mutnovskii Field that

Table 1. The monthly mean of H_2 vol % dissolved in the heat carrier at well 016 of the Mutnovskii Field

Year	N	m	σ
2004	6	2.18	0.49
2005	7	1.92	0.68
2006	9	3.74	1.22
2007	10	4.09	0.64
2008	7	3.17	0.66
2009	6	3.62	0.82
2010	4	4.66	1.56
2011	7	4.47	1.37
2012	7	3.85	0.88
2013	7	2.56	0.89
2014	6	8.37	4.24

N is the number of measurements per annum, m is the mathematical expectation, and σ is the rms deviation.

supply the geothermal power station (GeoPS) has been conducted since 2004. The Mutnovskii Field lies at the base of the eponymous volcano 76 km north of Petropavlovsk-Kamchatskii (see Fig. 1). The field is at the intersection of several sets of fissures, with some of these possibly extending well beneath Mutnovskii Volcano. The geothermal reservoir is supplied both by the meteoric water that comes from around the Mutnovskii crater and by an endogenous component.

The gas composition was found following the technique outlined in (Nikitina et al., 1989; Maksimov et al., 2011). Considering that the steam phase of the heat carrier has a total content of all gases, apart from steam, that amounts to a few tenths of a percent, while the concentrations of individual components in the gas mixture are still lower, for greater convenience and clarity we decided to calculate the concentrations as the volume and weight percentages for components of a “dry” gas, that is, for the gas mixture minus water.

VARIATIONS IN A RN IN SUBSOIL GAS AND THE VOLUME CONCENTRATION OF HYDROGEN IN THE GAS COMPOSITION OF THE HEAT CARRIER AT THE MUTNOVSKII GEOPS FOR THE LAST DECADE

Continuous well-recorded time series of subsoil Rn concentration at sampling rates of 10 to 30 min were acquired after digital radiometers were installed in October 2000. Some sample data for 2007 are shown in Fig. 2. The data for the 15-year period were corrected for air pressure and averaged by a 12-hour window with subsequent smoothing by a moving average of five data points in order to filter out the “high-frequency” component (Firstov, 2014).

It can be seen from Fig. 2 that the A Rn dynamics clearly shows a yearly component due to seasonal variation in the temperature of the sun-affected zone in unconsolidated deposits and a component that is due to ground-water-table (GWT) changes. This zone is frozen in the autumn and winter and its permeability is diminished, resulting in increased A Rn in the WSZ. In the spring, when the air temperature rises above zero centigrade, the infiltration of thaw water causes the GWT to rise; this reduces the A Rn by 20–25%. The subsequent decrease in the GWT is accompanied by an increasing column of subsoil atmosphere in unconsolidated deposits and a decreasing A Rn in the WSZ. In Kamchatka there are two well-pronounced periods of rising GWT, viz., in the spring and in autumn (Firstov and Rudakov, 2003). We studied long-period variations by subtracting the seasonal component from the A Rn time series following the additive model as set forth by Box and Jenkins (1970).

It was shown in (*Geotermicheskie* ..., 1986) that the Mutnovskii Field has increased concentrations of H_2 in the heat carrier compared with the other steam and hydrothermal fields in Kamchatka. In its origin the H_2 gas comes from depths, hence its variations in the dissolved gas of the heat carrier reflect not only the processes that are occurring in the geothermal reservoir, but also the geodynamic setting of the region. The gases that are dissolved in the heat carrier at all wells in the Mutnovskii Field show considerable variations in the volume fraction of H_2. This is especially noticeable at well 016, which is one of the more productive wells; it yields discharges of a steam–gas mixture at 13.4 kg/s with a steam content of 97%. Gas has been regularly sampled at the well once a month since 2004. We calculated the mean and the rms deviation of the volume fraction of H_2 in yearly intervals (Table 1). The fraction was about 2% in 2004–2005, increasing to reach 4% during the subsequent 2 years. After a drop in 2010, the volume fraction of $\bar{H}_2$ increased to 4.5% with subsequent decay in 2013 to nearly the initial value (in 2004). The sudden spike (8.4%) in 2014 was all the more unexpected against this background.

LARGE EARTHQUAKES IN THE NORTHWEST CIRCUMFERENCE OF THE PACIFIC OCEAN DURING THE LAST 15 YEARS

The seismicity in the subduction zone near Kamchatka is controlled by the interaction between the Eurasian and the Pacific plates; the epicenters of larger earthquakes are on the Pacific seafloor and far from the recording 1 stations. It follows from (Makarov, 2011; Firstov et al., 2011) that 65% of all M > 5.5 earthquakes whose hypocenters were in the subduction zone beneath the Avacha Bay were preceded by bay-shaped precursors in the field of soil Rn with advance times of 1 to 8 days. At the same

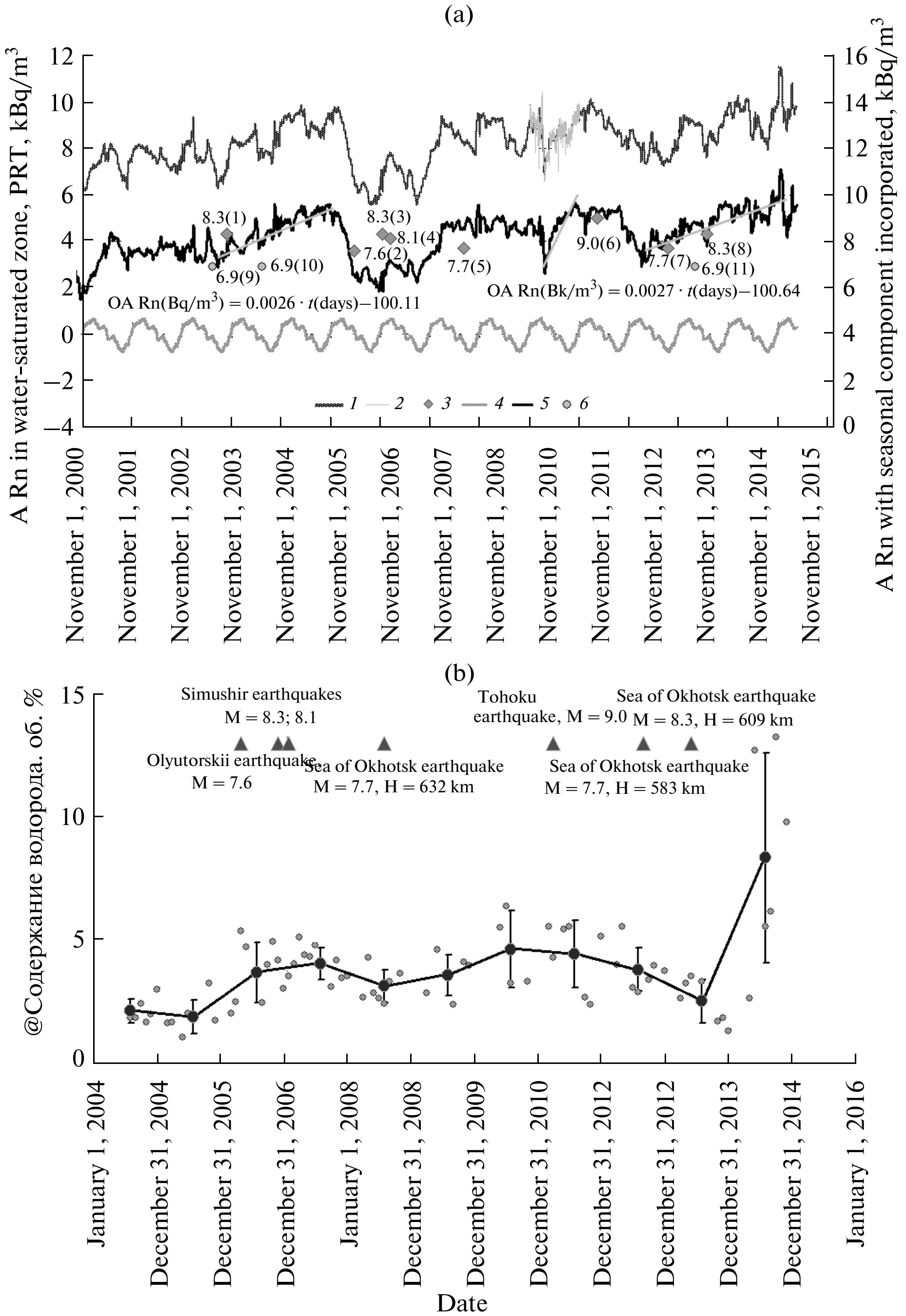

Fig. 2. The A Rn time series in the water-saturated zone (3.5 m depth) at the PRT site as smoothed by a moving average in a 5-day window, an additive seasonal model and curve with seasonal component subtracted (a), variations in the volume fraction of H_2 at well 016 in the Mutnovskii Geothermal Field (b).

(1) averaged data, (2) raw data, (3) M > 7.5 earthquakes along the northwest circumference of the Pacific Ocean, (4) additive seasonal model, (5) curve of A Rn with seasonal component subtracted, (6) M > 6.5 earthquakes beneath Kamchatka.

time, one can detect multiyear trends in a long time window (15 years) that correlate with geodynamic processes in the subduction zone along the northwest circumference of the Pacific Ocean (Firstov, 2014).

We scanned the NEIC catalog to select large (M > 7.5) earthquakes that occurred along the northwest circumference of the Pacific Ocean at depths of 0 to 700 km in an east–west strip 38°–61° N. The strip includes Japan, the Kuril Islands, Kamchatka, and the Sea of Okhotsk for the period between November 1, 2000 and April 1, 2015. Eight earthquakes occurred during this time span, of which three (in the Sea of Okhotsk) occurred at depths

Table 2. The basic parameters of M > 7.5 earthquakes that occurred along the northwest circumference of the Pacific Ocean and M > 6.5 earthquakes that occurred in the Benioff zone beneath Kamchatka

No.	Date	Time, hh:mm:ss	Coordinates		*H*, km	M	Epicentral area
			φ	λ			
M > 7.5							
1	25.09.2003	19:50:06	41.83	143.83	33	8.3	Tokachi-Oki, Japan
2	20.04.2006	23:52:02	60.94	167.14	22	7.6	Olyutorskii, northern Kamchatka
3	15.11.2006	11:14:13	46.58	153.27	39	8.3	Simushir I., Middle Kurils
4	13.01.2007	04:23:21	46.23	154.55	10	8.1	
5	05.07.2008	02:12:04	53.88	152.89	632	7.7	Sea of Okhotsk earthquake
6	11.03.2011	05:46:24	38.10	142.85	24	9.0	Tohoku, Japan earthquake
7	14.08.2012	02:59:38	49.80	145.07	583	7.7	Sea of Okhotsk earthquake
8	24.05.2013	05:44:48	54.89	153.22	609	8.3	Sea of Okhotsk earthquake
M > 6.5							
9	16.06.2003	22:08:02	55.49	159.99	175	6.9	Kamchatka region
10	10.06.2004	15:19:57	55.68	160.0	189	6.9	
11	28.02.2013	14:05:50	50.94	157.34	41	6.9	

φ is north latitude in degrees, @λ is east longitude in degrees; M is NEIC (National Earthquake Information Center) magnitude, *H* is depth of focus.

that were greater than 550 km. As well, M > 6.5 earthquakes occurred in the Benioff zone beneath Kamchatka. Three events occurred during the period of interest, of which two were deeper than 170 km (Table 2).

Three M > 7.5 earthquakes occurred during the period from April 2006 to January 2007, viz., one in northern Kamchatka (the Olyutorskii M 7.6 event, see Table 2, no. 2) and two in the Middle Kuril Islands (nos. 3 and 4 in Table 2, the so-called Simushir earthquakes with M = 8.3 and 8.1). These can be treated as a sequence of events like those that have been identified for large earthquakes in the Kuril–Kamchatka zone during the 1914–1982 period (Sobolev, 1994). The A Rn began to increase 2.5 years prior to the Olyutorskii earthquake, this was followed by a sharp drop of ~30% during the 3 months immediately before this seismic event. It should be noted that this increasing trend started at the time of the M 8.3 Tokachi-Oki, Japan earthquake (see Table 2, no. 1). This low level in the A Rn persisted for almost 18 months (see Fig. 2).

The M 7.7 Sea of Okhotsk earthquake in July 2008 (see Table 2, no. 5) was followed by the Tohoku, Japan mega-earthquake (M = 9.0) at a distance of 2100 km from the recording site on March 11, 2011 (see Table 2, no. 6). This too was preceded by a trend of increasing A Rn, which started in March 2010 and had continued for 8 months, until November 2010 (see Fig. 2a).

A trend of increasing A Rn has been observed from early 2012 up to the present, with two deep-focus Sea of Okhotsk earthquakes occurring in August 2012 upon this background (M = 7.7 in May 2013 and M = 8.3 in May 2013). The linear relationships that are fitted to the increasing tendency of A Rn for the first case are rather similar at present, viz., A Rn ($\mathrm{Bq/m^3}$) – 0.0026 · *t* (days) – 100.11 (before the Olyutorskii earthquake) and A Rn ($\mathrm{Bq/m^3}$) = 0.0027 · *t*(days) – 100.64 (at present). The three M 6.9 earthquakes that occurred in the Kamchatka area are not seen in the long-period variations of A Rn.

The variations in the volume fraction of $\overline{\mathrm{H}}_2$ at well 016 in the Mutnovskii Field show some relationship to large earthquakes that occurred along the northwest circumference of the Pacific Ocean. The highest values of $\overline{\mathrm{H}}_2$ occurred simultaneously (within a year) with the M > 8 Simushir and Tohoku earthquakes. The timing of the deep-focus Sea of Okhotsk earthquakes was concurrent with lower values of $\overline{\mathrm{H}}_2$ (see Fig. 2b).

RESULTS AND DISCUSSION

According to the classical concept (Novikov, 1989; Rudakov, 1992), as well as according to the contemporary ideas about the great effects that are exerted by subsoil gases due to micro-bubble buoyancy (the theory of a "geogas") in the WSZ on the migration of Rn, one can conclude that the controlling factor is permeability, which depends on the soil properties and soil structure, as well as the presence of an aquifer. The leading mechanism that operates in the WSZ to transport Rn toward the ground surface is a flow of gases in the form of microbubbles (Varhegyi 2 et al., 1986; Ivanova, 1999; Etiope and Martinelli, 2002). According to recent research, at depths of a few thousand meters the bubbles of transporting gases ($\mathrm{H_2}$,

CO_2, and CH_4) of diameters between 10^{-2} and -10^{-10} mm provide the leading agent by which heavy inert gases like He and Rn migrate.

The PRT station is in the zone of dynamic influence of a fault; the boundary of that zone can be fairly clearly discerned from geophysical data. The zone can be viewed as a fluid-rich reservoir where underground aquifer horizons are discharged. Seismic prospecting surveys have identified two layers with different physical and lithologic properties beneath the PRT: a soil–pyroclastic cover with $h = 1.8–2.7$ m and a layer of sand–clay deposits of alluvial origin with $h = 1.6–9$ m thick. The latter layer is underlain by a coarse rudaceous material with a sand filler of alluvial and fluvioglacial origin, fQII-III. The bulk of the Rn enters unconsolidated deposits (which have a very low concentration of Ra) from deeper layers owing to the 2 buoyancy of microbubbles in the discharge zone of underground aquifer horizons. The hydrological features of the PRT area and the recording in the WSZ suggest that the Rn flow toward the ground surface forms under the action of stresses and strain in the large geoblock that hosts most of the Paratunka Geothermal Field (Firstov et al., 2014).

Similarly to other gases, hydrogen in the heat carrier gas of the Mutnovskii Field responds to changes in crustal stress; its behavior reflects the geodynamic regime of the area. That this must be the case is shown by a decreasing CO_2/H_2S ratio, concurrently with the increase in the concentration of H_2. A rearrangement of the regional stress field probably affects the dynamics of both dissolved gases in the heat carrier and of subsoil gases.

The mechanism of long-term trends in the dynamics of A Rn is likely to be due to a changing stress field in the subduction zone of the northwest flank of the Pacific Ocean; the A Rn trend as observed at PRT since November 2012 provides evidence of an $M > 7.5$ earthquake that may occur within the future 18 months. It is surmised that the likely location for the expected earthquake can be the segment between the Shipunskii Peninsula and Shiashkotan Island, Middle Kurils, where the highest probability of an $M > 7.7$ earthquake exists for the period from September 2013 to August 2018, according to the long-term forecast of Fedotov et al. (2012).

REFERENCES

Avdualiev, A.K., Voitov, G.I., and Rudakov, V.P., A radon precursor to several large earthquakes in Central Asia, *Dokl. Akad. Nauk SSSR*, 1986, vol. 291, no. 4, pp. 924–927.

Box, G.E.P. and Jenkins, G.M., *Time Series Analysis, Forecasting and Control*, San Francisco: Holden Day, 1970.

Etiope, G. and Martinelli, G., Migration of carrier and trace gases in the geosphere: An overview, *Phys. Earth Planet. Int.*, 2002, vol. 129, nos. 3–4, pp. 185–204.

Fedotov, S.A., Solomatin, A.V., and Chernyshev, S.D., A long-term earthquake forecast for the Kuril-Kamchatka arc for the period from September 2011 to August 2016. The likely location, time, and evolution of the next great earthquake with M ? 7.7 in Kamchatka, *J. Volcanol. Seismol.*, 2012, vol. 6, no. 2, pp. 75–99.

Firstov, P.P., Variation in radon activity in subsoil gas before the Kronotskii earthquake, in *Kronotskoe zemletryasenie na Kamchatke 5 dekabrya 1997 goda: predvestniki, osobennosti, posledstviya* (The Kronotskii, Kamchatka Earthquake of December 5, 1997: Precursors, Features, Impact), Gordeev, E.I. and Ivanov, B.V., Sci. Eds., Petropavlovsk-Kamchatskii: IKGA, 1998, pp. 170–176.

Firstov, P.P., Possible prediction of large earthquakes from observations of radon monitoring at the Petropavlovsk-Kamchatskii Geodynamic Test Site, *Vestnik KRAUNTs, Nauki o Zemle*, 2014, no. 1, issue 23, pp. 232–245.

Firstov, P.P. and Rudakov, V.P., Results from recording of subsoil radon in 1997–2000 at the Petropavlovsk-Kamchatskii Geodynamic Test Site, *Vulkanol. Seismol.*, 2003, no. 1, pp. 26–41.

Firstov, P.P. and Shirokov, V.A., The dynamics of molecular hydrogen and its relationship to geological deformation at the Petropavlovsk-Kamchatskii Geodynamic Test Site as observed in 1999–2003, *Geokhimiya*, 2005, no. 11, pp. 1151–1160.

Firstov, P.P., Yakovleva, V.S., Shirokov, V.A., åt al., The nexus of soil radon and hydrogen dynamics and seismicity of the northern flank of the Kuril-Kamchatka subduction zone, *Annals of Geophysics*, 2007, vol. 50, no. 4, pp. 546–557.

Firstov, P.P., Makarov, E.O., and Malysheva, O.P., The behavior of soil radon at the Petropavlovsk-Kamchatskii Geodynamic Test Site as affected by the last precursory phase before earthquakes with magnitudes greater than 5.5 in the Avacha Bay area, in *Problemy kompleksnogo geofizicheskogo monitoringa Dal'nego Vostoka Rossii* (Problems in Multidisciplinary Geophysical Monitoring in the Russian Far East), *Proc. 3rd conf.*, Petropavlovsk-Kamchatskii, October 9–15, 2011, Chebrov, V.N., Sci. Ed., Obninsk: GS RAN, 2011, pp. 154–158.

Firstov, P.P., Akbashev, R.R., Makarov, E.O., and Parovik, R.I., The structure of upper geological sections beneath soil radon monitoring sites in the Petropavlovsk-Kamchatskii Geodynamic Test Site, in *Materialy ezhegodnoi konferentsii, posvyashchennoi Dnyu vulkanologa "Vulkanizm i svyazannye s nim protsessy"* (Proc. annual conf. devoted to Volcanologist's Day "Volcanism and Related Processes"), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2014, pp. 242–250.

Firstov, P.P., Makarov, E.O., and Akbashev, R.R., Monitoring of soil gas concentrations at the Petropavlovsk-Kamchatskii Geodynamic Test Site for earthquake prediction purposes, *Seismicheskie Instrumenty*, 2015, no. 1, pp. 53–73.

Geotermicheskie i geokhimicheskie issledovaniya vysokotemperaturnykh gidroterm (Geothermal and Geochemical Research in High Temperature Hydrothermal Occurrences), Moscow: Nauka, 1986.

Gufel'd, I.L. and Novoselov, O.N., *Seismicheskii protsess v zone subduktsii. Monitoring fonovogo rezhima* (The Seismic Process at Subduction Zones. Monitoring of the Background Regime), Moscow: MGUL, 2014.

Ivanova, T.M., *Modeling the Transport of Radon in a Rock Massif*, Extended Abstract of Cand. Sci. (Tech.) *Dissertation,* Moscow, 1999, 25 p.

Larin, V.N., *Nasha Zemlya (proiskhozhdenie, sostav, stroenie i razvitie iznachal'no gidridnoi Zemli)* (Our Earth: Origin, Composition, Structure, and Evolution of an Originally Hydrid Earth), Moscow: Agar, 2004.

Letnikov, F.A., The fluid regime of endogenous processes in continental lithosphere: Implications for metallization, in *Problemy global'noi geotektoniki* (Problems of Global Geotectonics), Rundkvist, D.V., Sci. Ed., Moscow: GEOS, 2000, pp. 204–224.

Makarov, E.O., Precursory anomalies of large (M > 5.5) earthquakes in the Avacha Bay in the field of soil radon as observed at the Petropavlovsk-Kamchatskii Geodynamic Test Site, in *Geologiya v razvivayushchemsya mire* (Geology in a Changing World), Proc. Intern. conf. of students, postgraduate students, and young scientists, town of Perm, April 20–24, 2011, Baturin, E.N., Sci. Ed., Perm University Press, 2011, pp. 347–349.

Makarov, E.O., Firstov, P.P., and Voloshin, V.N., An instrumentation set for recording the concentrations of subsoil gases with a view to searching for precursory anomalies of large earthquakes in southern Kamchatka, *Seismicheskie Instrumenty*, 2012, vol. 48, no. 1, pp. 5–14.

Maksimov, A.P., Firstov, P.P., Chernev, I.I., and Shapar', V.N., A method for evaluating the fraction of meteoric water in the heat carrier at the Mutnovskii geothermal power station, *Materialy ezhegodnoi konferentsii, posvyashchennoi Dnyu vulkanologa* (Proc. Annual Conf. Devoted to Volcanologist's Day), Petropavlovsk-Kamchatskii: IViS DVO RAN, 2011, pp. 146–149.

Nikitina, L.P., Menyailov, I.A., and Shapar', V.N., Modified methods for sampling and analysis of volcanic gases, *Vulkanol. Seismol.*, 1989, no. 4, pp. 3–15.

Novikov, G.F., *Radiometricheskaya razvedka* (Radiometric Prospecting), Leningrad: Nauka, 1989.

Rudakov, V.P., *The Dynamics of Fields of Subsoil Radon in Seismic Regions of the Former Soviet Union*, Extended Abstract of Doct. Sci. (Phys.–Math.) *Dissertation*, Moscow, 1992, 37 p.

Sobolev, G.A., On the relationship between large earthquakes occurring in the Kuril–Kamchatka zone, in *Federal'naya sistema seismologicheskikh nablyudenii i prognoza zemletryasenii*, (Federal System for Seismological Observations and Earthquake Prediction), IAB, Shikotan Earthquake of October 4(5), 1994, extra issue, 1994, pp. 68–70.

Spivak, A.A., Sukhorukov, M.V., and Kharlamov, V.A., The emanation of radon ^{222}Rn in relation to depth, *Dokl. Akad. Nauk*, 2008, vol. 420, no. 6, pp. 825–828.

Steinitz, G., Begin, Z.B., and Gazit-Yaari, N., A statistically significant relation between radon flux and weak earthquakes in the Dead Sea Rift Valley, *Geology,* 2003, vol. 31, pp. 505–508.

Syvorotkin, V.L., *Glubinnaya degazatsiya Zemli i global'nye katastrofy* (Deep-Seated Degassing in the Earth and Global Disasters), Moscow: OOO Geoinformtsentr, 2002.

Utkin, V.I. and Yurkov, A.K., Radon and the problem of tectonic earthquakes, *Vulkanol. Seismol.*, 1997, no. 4, pp. 82–94.

Varhegyi, A., Baranyi, I., and Somogyi, G., A model for the vertical subsurface radon transport in "geogas" microbubbles, *Geophys. Trans.*, 1986, vol. 32, no. 3, 2
pp. 235–253.

Voitov, G.I., On the problem of hydrogen breathing in the Earth, in *Degazatsiya Zemli: geodinamika, geofluidy, neft' i gaz. Materialy mezhdunarodnoi konferentsii pamyati akademika P.N. Kropotkina* (Degassing of the Earth: Geodynamics, Geological Fluids, Oil, and Gas, Proc. intern. conf. in memory of Academician P.N. Kropotkin), Moscow: GEOS, 2002, pp. 24–30.

Translated by A. Petrosyan

SPELL: 1. seafloor, 2. microbubbles