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Increased Radon and Thoron in the Verkhne-Paratunka Hydrothermal System, Southern Kamchatka Prior to the Catastrophic Japanese Earthquake of March 11, 2011

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Abstract—This paper reports results from the first-ever simultaneous measurements of the volumetric activities of radon and thoron in subsoil gas and in the near-surface air. These measurements were in progress during the precursory period and occurrence of the March 11, 2011 disastrous earthquake in Japan at a distance of 2000 km from the observation site. The earthquake was preceded by an anomalous increases in radon and thoron activity in the subsoil gas, and afterwards in the air, 44.7 days prior to the earthquake. The anomalous values persisted for 24.9 days. We discuss the features and causes of these increases.

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INTRODUCTION

The decay of the long-lived radioactive elements uranium-238 and thoron-232, which are widely abundant in the Earth's crust, constantly generates radon and thoron as radioactive emanations. Having the properties of inert gases, they migrate to the ground surface and enter the atmosphere (Larionov, 1963; Junge, 1963). The concentration of the emanations in subsoil gas depends, among other things, on stress and strain in the rocks. This enables one to use them, especially radon, as an indicator of geodynamic processes (Rudakov, 2009; Utkin and Yurkov, 2010) and of the intensity of inter-geosphere interactions at the crust–atmosphere interface (Spivak et al., 2009), as well as for structural mapping of the geological medium (Rudakov et al., 1995; Dekhandshutter et al., 2002; Koval' et al., 2006).

Studies of preseismic subsoil radon variations are widely popular at present. The results that have been obtained thus far notably include an increase in radon activity 90 to 100 days before an earthquake during extension in near-surface rocks (Utkin et al., 2006; Utkin and Yurkov, 2010). Anomalous radon behavior can be observed at very long distances from the epicenters, for example, there is a case where it was recorded at a distance of 3400 km before a magnitude 7.3 earthquake (Rudakov, 2005). Such cases can be explained by the concept of remote precursors: disturbances in physical fields can be recorded before large earthquakes at very long epicentral distances (Sidorin, 1980; Kiryukhin et al., 2006; Sobisevich et al., 2009; Balasanyan, 2005; Kalinina et al., 2000).

Joint measurements of subsoil radon and thoron before earthquakes are not common. We are aware of two cases of such measurements (Utkin et al., 2006; Yang et al., 2005). The results that were reported by these authors provide evidence of preseismic increases in the activities of both emanations. It therefore seems reasonable that both should be measured simultaneously.

As radon and thoron enter the atmosphere, they are mixed with air. As a result, their concentrations are reduced and measurements become more difficult, especially for thoron, which has a short half life. It is probably for this reason that there have been few studies on the detection of preseismic disturbances in radon in near-ground air, and none at all for thoron. We know of a case in which radon activity increased at a height of 5 m from the ground surface approximately 2 months before the $M_w = 6.9$ Japanese earthquake of January 17, 1995 (Yasuoka et al., 2006). No simultaneous measurements of radon and thoron in subsoil gas and in near-ground air have ever been carried out. Such measurements would be important to provide some clue to the understanding of how the lithosphere acts on the atmosphere during the release of these emanations from earth, which result in increased air ionization and thus give rise to atmospheric electrical and ionospheric precursors of earthquakes.

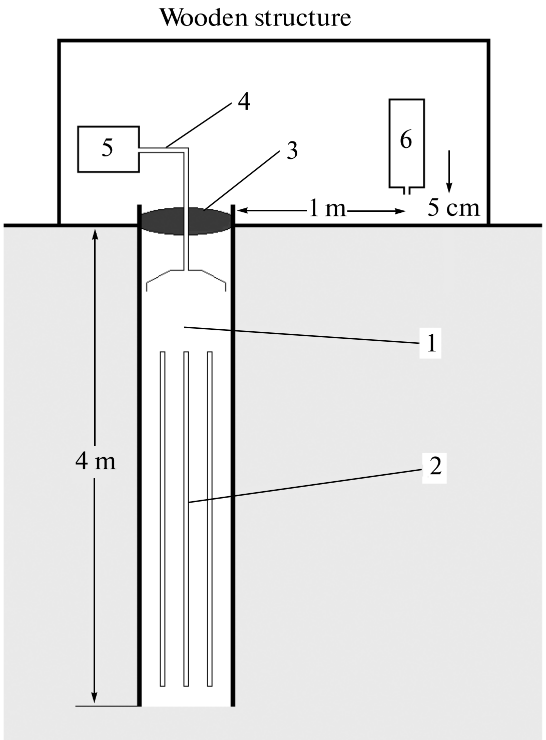

Fig. 1. A diagram that shows the method of measurement. (1) drilled well, (2) aperture filter, (3) well sealing, (4) pipe for gas pumping, (5, 6) RRA-01M-03 and SRS-1 radiometers.

Similarly to the other precursors, anomalous disturbances of subsoil radon do not occur uniformly, are rather episodic, and are frequently complicated with variations that come from other sources. Nevertheless, every fact about such disturbances, especially as recorded before disastrous earthquakes and together with thoron, should be described and studied.

The present paper reports results from joint measurements of radon and thoron activity in a 4 m deep dry well and in the air near the ground surface around the well. The measurements were being conducted during the precursory period and occurrence of the disastrous Japanese earthquake of March 11, 2011. That event was preceded by recorded anomalous increases in the activity of the emanations in the well, and afterwards, in the air. Some of the features and causes of these increases are considered below.

METHOD OF MEASUREMENT

The activity of radon (A Rn) and thoron (A Th) was measured at the Karymshina site in southern Kamchatka (52.826° N, 158.131° E) by the Kamchatka Branch of the Geophysical Service of the Russian Academy of Sciences from December 27, 2010 to May 20, 2011. The site is in the area of the Verkhne–Paratunka hydrothermal system, whose structural features are largely controlled by block tectonics. The blocky structure arose via the combination of movements along systems of long-lived, differently striking faults. Most of the faults have surface expression and are accompanied by zones of mylonization and hydrothermally altered rocks (Serezhnikov and Zimin, 1976).

Our measurement technique involved gas pumped from a sealed well that is a few meters deep, thus considerably reducing the effects of atmospheric pressure and tidal strain changes in rocks on the behavior of subsoil radon and thoron. At the same time, since the rate of migration of these emanations increases, the consequence is that the rock volume from which the emanations come to the well increase too; thus, the method of measurement has an enhanced sensitivity (Utkin et al., 2006; Utkin and Yurkov, 2010).

The measurement scheme is shown in Fig. 1. The well is encased in a pipe that is 0.1 m in diameter and 4 m long, with an aperture filter being made in the pipe along a distance of 1–3.9 m as measured from the pipe top. The gas was sampled from a depth of 0.5 m in the pipe. The sampling reduced the pressure in the pipe by 7.6%. Simultaneously, the activity of radon and thoron was measured at a height of 5 cm above the ground at a distance of 1 m from the well in a wooden structure. Under these conditions the emanations have little air in them; this facilitates the measurement. An automated RRA-01M-03 radiometer was used in the well and an SRS-1 radiometer in the air around the well; both were manufactured by Zashchita NTM Ltd. The measurements were conducted once and twice an hour, respectively. A climatic chamber that was installed along with the SRS-1 radiometer was used to measure atmospheric pressure, temperature, and the relative humidity of the air that was pumped in at the ground surface. The radiometer had an independent power supply whose voltage was monitored, and was normal during the measurements.

The geologic column at well 99-8, which was drilled 9 m from the measuring well to a depth of 19 m, consisted of the following rocks: cobble–pebble deposits with a sand-clay filler (0 to 5 m), blocks mixed with rock waste and a clay filler (5 to 14 m), and cobble–pebble deposits with a sand filler (14 to 19 m). The static water table in the well was 13.7 m. The observing well was thus dry and inside near-surface sedimentary rocks.

RESULTS AND DISCUSSION

Figure 2 shows a time series of measured quantities. Anomalous increases in the activity of radon and thoron at the well (anomaly A) were observed from 14:00 January 25 to 21:00 February 11 (UTC), and increases in the air near the ground surface around the well occurred from 15:00 February 8 to 09:00 February 19 (anomaly B). There have been no other disturbances in the activity of

An estimate of the Spearman rank correlation coefficient, r_s, and its significance level p; the correlation between emanation activity and air pressure, P, pressure change, ΔP, for 0.5 h, relative air humidity, F, and air temperature, T, during the anomaly in the air

Emanation activity	P		ΔP		F		T	
	r_s	p	r_s	p	r_s	p	r_s	p
A Rn	–0.34	<0.001	–0.36	<0.001	0.26	<0.001	0.06	0.18
A Th	–0.41	<0.001	–0.32	<0.001	0.25	<0.001	0.22	<0.001

In all cases the number of pairs of correlated values is 517.

these emanations during the time in which the measurements were made. We now consider the anomalies.

The emanation anomaly in the well (anomaly A) started in an increase of A Th that was soon followed by an increase in A Rn. The disturbed behavior of both of these quantities came to an end almost simultaneously. The anomaly was not accompanied by large air pressure decreases that lasted several days (see Fig. 2). Such decreases arise during the passage of a cyclone and can cause a considerable increases in the activity of subsoil radon (Spivak et al., 2009; Firstov and Rudakov, 2003; Nishimura and Tatsura, 1990) and thoron. The anomaly was unconnected with a decrease in the air temperature, which lasted 6.8 days after the decrease stopped. The decrease involved daily fluctuations of considerable amplitude. The fluctuations were especially large on January 25 and 26, when the lowest temperature values were recorded, –15° and –17°C. These, and subsequent slightly higher temperatures that were observed on the background of a slow return to the former level (about +2°C), were observed during the daily lows. These daily fluctuations in the air temperature in the wooden structure could not affect the supply of emanations into the well, since associated fluctuations in soil temperature are unobservable at a depth as shallow as 0.8 m (Khrgian, 1978), while the aperture filter was 1–3.9 m below the ground surface.

There had been no increase in local seismicity either before the emanation anomaly or during it; three weak earthquakes (energy class $K_s \leq 10.5$) occurred within 200 km of Karymshina. Two larger earthquakes ($K_s = 11.5$ and 11.6) which occurred 190 km and 140 km from the observation site after the anomaly on February 23 and 28 did not affect the behavior of subsoil radon and thoron before the Japanese event (see Fig. 2).

The precursory process of a large earthquake involves ground deformation. The theoretical distance of precursory strain changes $R = e^M$ (km) (Dobrovol'skii, 1991) is 8100 km for the Japanese earthquake. The Karymshina site is 2000 km of its epicenter, so is safely within that distance.

The disastrous Japanese earthquake (magnitude M_w = 9.0) could have affected the behavior of seismic processes in adjacent and remoter regions, including the earthquake-generating zone off eastern Kamchatka. Fedotov et al. (2012) noted a likely relationship between the earthquake swarm that occurred east of the Avacha Bay during March 4 through 19, 2011 and the earthquake under discussion. The swarm may have been a remote foreshock and aftershock process that accompanied the Japanese earthquake and might indicate very high stress buildup in the segment of the earthquake-generating zone adjacent to the Avacha Bay (Fedotov et al., 2012). The Karymshina site is 30 km from the shore of the bay. The anomaly in the well began 44.7 days before the Japanese earthquake, when seismic noise in the range of periods of a few minutes experienced a considerable increase at the Petropavlovsk station (43 km from the site) at approximately 45 days before the earthquake (Sobolev, 2011). Short-lived crustal strain structures experienced a sudden change in British Columbia, Canada at a distance of over 8000 km from the epicenter on February 18, 2011, indicating a change in the application of external loading (Vartanyan et al., 2013).

The above discussion leads us to the inference that the emanation anomaly in the well that lasted 17.3 days was related to the precursory processes of the March 11, 2011 disastrous earthquake in Japan.

Radon and thoron have similar physical and chemical properties, except that their half-lives are 3.825 and 55.6 s, respectively. Owing to this small value, thoron cannot migrate far from its place of generation and its mass transport is surficial only. According to Guedalia et al. (1970), thoron enters the atmosphere from a soil layer that is 6 cm thick, with up to 75% of the emanation being due to the upper 2 cm. It follows that thoron entered the well from a thin layer of sedimentary rock just around the casing pipe, hence the layer was thinner than 10 cm.

The anomaly in the well is a combination of increases in A Th and A Rn that have different amplitudes and durations (see Fig. 2). The increase in A Th can be explained by increased emanation from the sedimentary rocks immediately around the casing pipe due to extension, when relative micro-displacements of rock fragments occur, contact surfaces in the immediate proximity become open, and more thoron is released into the pore space. The complex rupture dynamics and the appear-

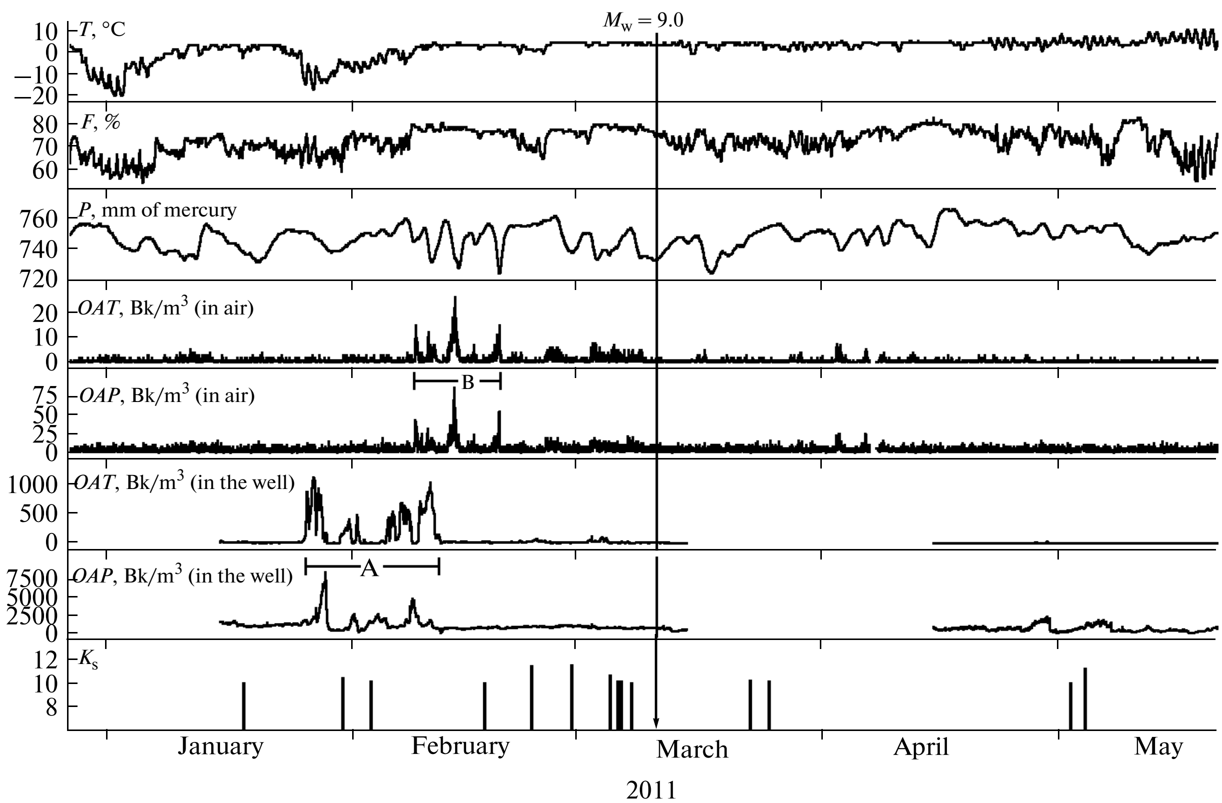

Fig. 2. Variations in the air temperature, T, air relative humidity, F, air pressure, P, thoron activity, TA, and radon activity, RA, during measurements.
Bottom: earthquakes with energy class $K_S \geq 10.0$ that occurred within 200 km of the Karymshina station (data were supplied by the Kamchatka Branch of the Geophysical Service of the Russian Academy of Sciences). The vertical arrow marks the time of the disastrous Japanese earthquake. A denotes the emanation anomaly in the well, B denotes that in the air.

ance of contacts between fragments with different shapes, a wide range of sizes, and unequal concentrations of thoron-232 in mineral grains in combination will produce increases in A Th that would be different in amplitude and duration during the extension. It would be hard to imagine a factor that leads to higher concentrations of short-lived thoron in the well other than increased emanation from the rocks.

Figure 3a shows the cross correlation function for the activity of radon and thoron during the anomaly in the well. This function expresses the degree of correlation between their activities in relation to relative displacement over time. The greatest values are attained by this function at positive lags in the 12–32 h interval and are statistically significant. It can be seen in Fig. 2 that the A Th increases occurred before the A Rn increases, and that different A Th increases occurred in advance over the A Rn increases for different times. This produced the interval of the greatest values of this function.

Its long half-life value makes it possible for radon to move for considerable distances from its place of generation, while the fact that its increases were late can be explained by the idea that it comes from remoter rocks compared with thoron, including the ascent from greater depths. This must occur under the extension of sedimentary rocks, when lower density makes for greater permeability and a shorter time of radon migration. The remote sources that are referred to might be rock volumes with increased concentrations of clay, which occurs around the observing well, judging from the drilling results (see above). Clays frequently contain more uranium than coarser sedimentary rocks do (Bell, 1954). Calculations by Gofman and Perevalov (1984) show that increased sizes of isotropic homogeneous solid particles and the resulting increase in interparticle space reduces the emanation coefficient due to recoil atoms, which is the main producing factor at normal temperatures. In view of the above discussion, we should explain later radon increases in a time interval by the occurrence of several rock volumes of this type at different distances to the well-casing pipe.

Assuming that the above explanation of increases in radon and thoron activity in the well is true for the moment, one can hypothesize that the anomaly was probably caused by different (in intensity and duration) extensions of near-surface sedimentary rocks at the observation site.

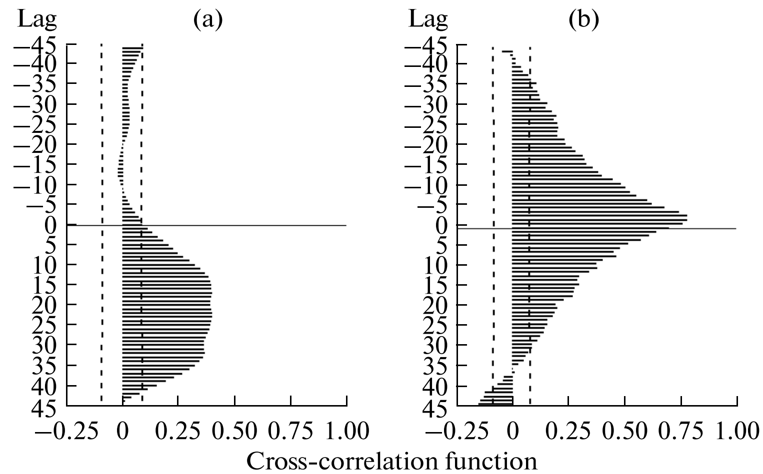

Fig. 3. The cross-correlation function for radon activity and thoron activity during the anomaly in the well (a) and in the air near the ground surface (b). The time series that was shifted was thoron activity. The lags were 1 and 0.5 hours, respectively. The dashed lines mark confidence boundaries at the 0.05 significance level.

The Spearman rank correlation coefficient for correlation between A Rn and A Th with a zero shift of the series during the anomaly in the well is 0.1, which is significant at the 0.05 level. The cross correlation function at zero lag (see Fig. 3a) is 0.09 at the 0.04 significance level. It thus appears that the estimates of strength and reliability for the correlative relationship between the simultaneous values of A Rn and A Th are nearly identical. It follows that the cross correlation function as depicted in Fig. 3a provides a realistic estimate of the relationship between the increases of the emanation activity over time.

The emanation anomaly in the air (anomaly B) began during the termination of the anomaly in the well, when considerable decreases in atmospheric pressure were observed due to three cyclones (see Fig. 2). The decreases reached 732, 728, and 724 mm of mercury, which means that these were deep cyclones (Khromov and Petrosyants, 1994). The anomaly in the air came to an end 19.8 days before the Japanese earthquake occurred.

The table shows estimates of the Spearman rank correlation coefficient and its significance level for the activity of emanations and atmospheric pressure, a pressure change for 0.5 h, relative humidity and temperature of the air during the anomaly. The highest correlation is that between the activity of the emanations and atmospheric pressure. It is highly significant and negative. The presence of this anomaly is explained by increasing concentrations of radon and thoron in the air as a result of gas being pumped away from the soil as the atmospheric pressure was decreasing. As atmospheric pressure increases, air enters soil capillaries and drives out the soil gas that contains the emanation (Styro, 1959). There is a correlation between the activity of emanations and atmospheric pressure variation that is similar to the preceding as to the strength, significance, and sign. This correlation shows that the increasing concentrations of the emanations in the air were also affected by the rate of decrease of the pressure and vice versa. There is a weak, but positive, correlation between the emanation activity and the relative humidity of air, as well as between air temperature and A Th. No correlation was observed between air temperature and A Rn.

The cross-correlation function for the activity of radon and thoron during the anomaly in the air is shown in Fig. 3b. The function has a well-defined statistically significant prominent maximum, which is equal to 0.78 for a lag of 1–1.5 h for thoron activity. The presence of such a maximum near the zero lag provides evidence of a common factor that operated to increase A Rn and A Th, consisting in decreases in atmospheric pressure during cyclones, with large amplitudes and rates of decrease in atmospheric pressure. The emanations then came into air from the uppermost layer of the soil where gases of atmospheric origin are in convection. The small lag of A Th increases was probably due to the rapid decay of thoron and thus a longer time to reach the maximum values at a height of 5 m above ground in the wooden structure, where no turbulence or convection occurs.

We note that the second and third largest increases in emanation activity in the air (see Fig. 2, anomaly B) did not cause a concurrent increase in the well. It follows that when full allowance for our method of measurement is made the decrease in the atmospheric pressure did not affect the behavior of radon and thoron in the well, thus providing an extra corroboration for the tectonic origin of the emanation anomaly in the well.

There have been other decreases in atmospheric pressure during the period of measurement in the air (nearly 5 months). One of these was a large decrease, to 725 mm of mercury, on March 18 (see Fig. 2). However, there have been no considerable increases in the activity of radon and thoron, apart from anomaly B. This shows that the anomaly in the air was most likely caused by the anomaly in the well. The latter anomaly was due to increased concentrations of radon and thoron in near-surface sedimentary rocks. Obviously, the concentrations also increased in the surface soil layer, but the supply into the atmosphere only occurred during large and rapid decreases in atmospheric pressure due to deep cyclones.

The maximum relative deformation in rocks due to surface waves that were excited by the Japanese earthquakes at the Petropavlovsk station (43 km from the Karymshina site) was 5.0×10^{-6} (Sobolev and Zakrzhevskaya, 2013), which is more than two orders of magnitude greater than the tide-induced deformation. However, the emanations in the well did not respond to the passage of these waves, which caused short-lived extensions and compressions in the surrounding sedimentary rocks. It is rather likely that the preseismic excitation in the rocks and the resulting emanation anomaly were caused by a slow stress change off eastern Kamchatka and that the 3D strainmeter that responded to this change was the Verkhne-Paratunka hydrothermal system, which has a complicated internal structure. This hypothesis is supported by the above-mentioned earthquake swarm east of the Avacha Bay (Fedotov et al., 2012) and the increase in low-frequency seismic noise as recorded at the Petropavlovsk station (Sobolev, 2011), as well as by the well-substantiated concept of tectonic precursors (Sobolev and Ponomarev, 2003), which do not arise at earthquake sources, but reflect stress changes in an extensive area.

CONCLUSIONS

We presented the first experiment on simultaneous measurements of the activity of radon and thoron in subsoil gas and in the near-ground air. The measurements were conducted in a dry well that was drilled in near-surface sedimentary rocks and at a height of 5 cm above the ground near the well. The measurements were made concurrently with the precursory period and the occurrence of the disastrous Japanese earthquake that occurred on March 11, 2011 at a distance of 2000 km from the observation site. This extraordinary event was preceded by anomalous increases in radon and thoron activity in the well, and subsequently in the air. The anomaly in the well began 44.7 days before the earthquake and lasted 17.3 days. The anomaly in the air occurred during the termination of the anomaly in the well and was caused by large and rapid decreases in atmospheric pressure that were due to the passage of deep cyclones. This anomaly came to an end 19.8 days before the earthquake and was most likely caused by the anomaly in the well.

The anomalous increase in thoron activity in the well can be explained by increased emanation from the sedimentary rocks around the casing pipe, while the radon anomaly was due to supply from remoter rock volumes where clay is abundant. These increases were probably caused by extension of near-surface sedimentary rocks at the observation site due to stress changes off eastern Kamchatka before the Japanese earthquake.

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