ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту, 2024, № 4 (108)

UDC 551.432:550.835.2(536.4)

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On the Issue of the Radon Activity of Tectonic Faults on the Qatar Peninsula

Purpose. The paper aims at providing the modern evaluation of radon activity in identified tectonic faults of the earth's crust based on archival data of radon measurements in groundwater which previously have been performed in the northern and eastern parts of the Qatar Peninsula. **Methodology.** The paper presents an additional extended justification for the application of an innovative technique for these conditions to identify the activity rate of tectonic faults in the rock foundation under the geological conditions of the Qatar Peninsula based on third-party measurements of radon in groundwater and using own universal Evaluation scale. **Findings.** A modern analysis of previously obtained results of radon measurements in groundwater of the Qatar Peninsula allowed us to suggest the orientation of tectonic fault directions in its northern and eastern parts and to additionally reveal the rate of their radon activity within the peninsula with a preliminary magnitude evaluation of displacement along the faults. A similar assumption was also proposed in the western part of the UAE adjacent to the peninsula, where the Barakah Nuclear Power Plant (BNPP) is located. This assumption is based on a certain similarity in the geological and tectonic conditions of the region. **Originality.** For the first time, the authors proposed the location of tectonic faults within the northern and eastern parts of the Qatar Peninsula according to radonometry performed for other purposes. We estimated their radon activity and the magnitude of movement along the faults. This implies increased safety during the construction and operation of various facilities, including a high degree of responsibility, particularly pipeline systems and transport communications that are important for the country's economy. **Practical value.** This technique can also be used in seismic monitoring for construction sites and in adjacent territories of other countries where similar explorations have not been conducted before.

Keywords: Qatar; radonometry; wells; radon measurements; tectonic faults

Introduction

The special properties of radioactive radon gas served as the basis for its use as one of the available indicators in establishing the activity rate of tectonic fault zones. Monitoring the stress state of the subsurface resources in such zones is necessary since various deformations of the earth's surface are observed near such zones. These processes lead to violations of the planned-high-altitude position and integrity of residential and public buildings, transport infrastructure facilities as well as structures of especially important energy facilities, such as nuclear power plants (NPP) [1]. In the numerous field studies during the 70–80s of the last century, a direct connection was established between the intensity of radon anomalies and geodynamic processes in tectonic fault zones. This phenomenon was the basis for organizing a fundamentally new direction of applied research in the field of engineering geology – structural-geodynamic mapping.

The peculiarities of radon (^{222}Rn) behavior in geological space have created conditions for continuous radon monitoring as one of the indicators of possible seismic events, for example, abnormally high or abnormally low concentrations of gas in periods preceding earthquakes. The importance of radon monitoring for earthquake forecast purposes has been repeatedly confirmed in practice including the infamous events in the Italian L'Aquila (Abruzzo) that occurred in April 2009. These events were predicted several months before by local seismologist Giampaolo Giuliani based on observations of variations in soil radon.

Despite numerous facts of fairly successful application of this method, radon as a possible indicator of changes in the stress state of the subsurface resources has so far received undeservedly very little attention. This especially concerned measurements of radon concentration in groundwater. However, in recent years, soil radon measurements for geodynamic research have already been consolidated in regulatory documents of several countries,

doi: https://doi.org/10.15802/stp2024/316330

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albeit with few reservations. The technique of measuring radon in groundwater for geodynamics and earthquake forecast has yet to prove its value, although individual research in this field has been conducted [4, 7, 8, 9, 13,14, 18, 19, 21, 22].

Purpose

The objective of this article is a modern evaluation of the radon activity in identified tectonic faults of the earth's crust based on open-source data of radon measurements in groundwater. These researches were previously carried out in the northern and eastern parts of the Qatar Peninsula by local research organizations. As well as justification for the application of the method for identifying the activity rate of tectonic faults in the specified area based on our own universal numerical scale.

Methodology

The Qatar Peninsula and the Gulf coastal areas have been studied in considerable detail for oil and gas exploration by various local and foreign organizations. Numerous large-scale geological, geotechnical, and geo-ecological explorations have been conducted both on land and in the waters. As a result, the geological structure of the peninsula has been studied quite fully and described in many works available for wide review and study [6, 10, 15, 17]. In particular, geological maps of the peninsula are shown in Fig. 1 and 2.

However, the authors could not find a sufficiently detailed tectonic map of the peninsula with the exact location of tectonic fault zones. Nevertheless, their presence in the northern part of the study area is beyond doubt and is confirmed by works [2, 11]. Indirect data can help clarify this situation, in particular, the results of radon measurements in groundwater at the specified territory.

Explorations to determine radon in groundwater on the peninsula and in the adjacent territory were carried out, but exclusively for environmental purposes [3, 12]. The last of the above-mentioned scientific articles is the most interesting in its results for this work. The explorations were carried out at a fairly high level, and the same is true for the equipment used. The following materials were taken from this article for study and analysis: Fig. 3, 4, and Table 1.

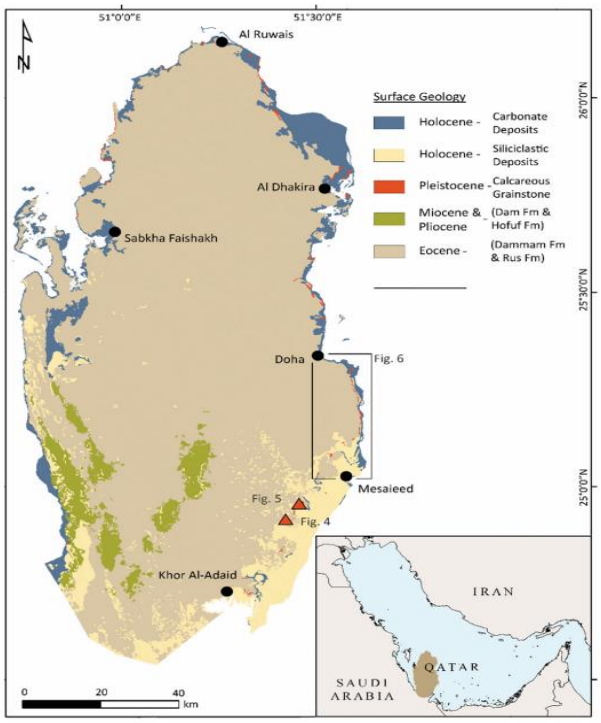

Fig. 1. The surficial geological map of Qatar after Cavelier et al. (1970) and Seltrust Engineering Ltd (1980) showing various localities discussed in the text. Inset: Location map showing Qatar in the context of the Arabian Gulf area (imagery data: ESRI 2005 ArcWorld Supplement). J.M. Rivers et al (2021)

doi: https://doi.org/10.15802/stp2024/316330

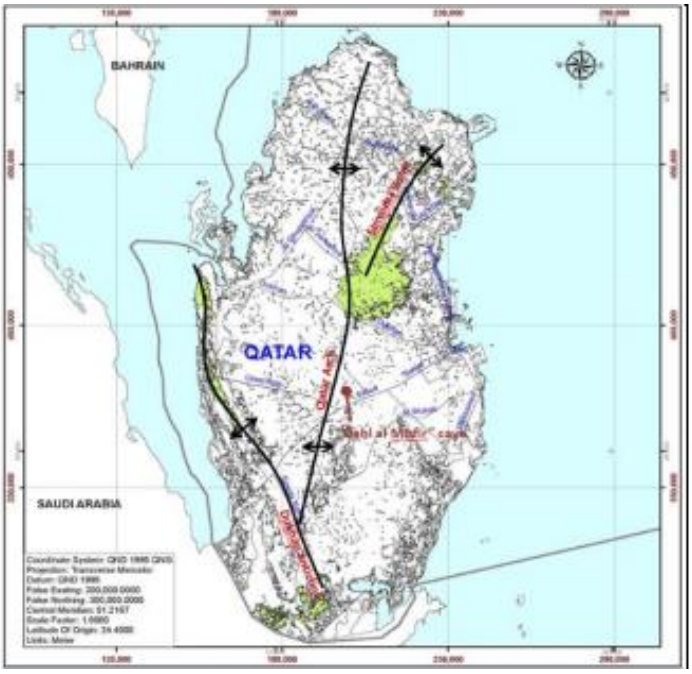

Fig. 2. Occurrences of the Rus Formation at the surface of Qatar in relation to the main structural features of the country (Qatar Arch, Simsima Dome and Dukhan Anticline). Jacques LeBlanc (2021)

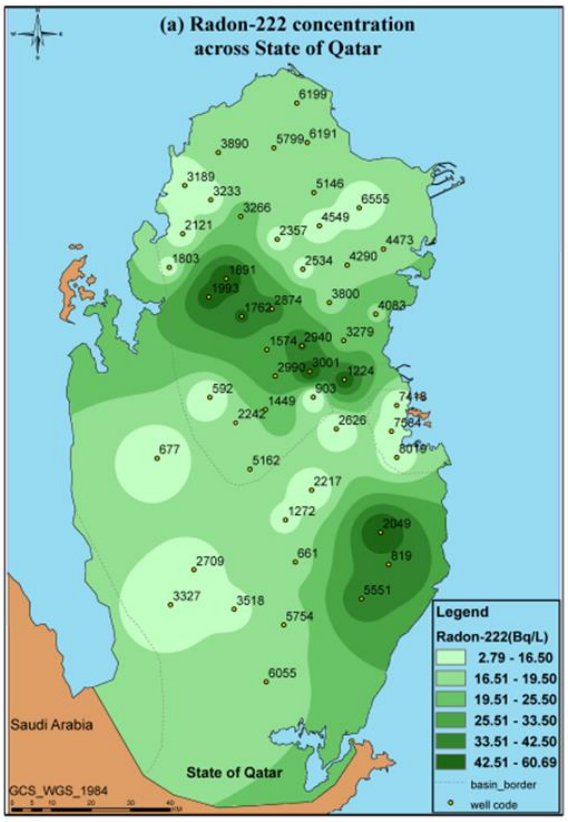

Fig. 3. The well location diagram and color gradation of zones based on radon content in groundwater. Manawi, Y. et al (2023)

Table 1

Results of radon measurements in wells on the peninsula. Manawi, Y. et al (2023)

Well Code	Radon Bq/L	Well Code	Radon Bq/L
592	5.57±0.64	3001	55.50±1.40
661	16.50±0.22	3189	7.550±1.720
677	5.16±0.69	3233	11.00±1.710
819	41.90±02.81	3266	21.200±2.070
903	2.71±0.20	3279	20.900±0.907
1224	52.40±2.63	3327	8.550±0.217
1272	12.40±1.50	3518	12.600±0.422
1574	28.90±0.925	3800	14.500±1.120
1762	45.30±1.32	3890	16.100±0.970
1803	11.900±0.948	4083	18.300±1.880
1891	58.800±2.760	4290	17.400±1.790
1993	49.400±4.010	4473	18.500±1.100
2049	60.700±13.400	4549	9.00±0.441
2121	9.870±0.889	5146	17.700±2.540
2217	6.900±0.764	5162	15.600±1.560
2242	14.400±1.380	5551	39.100±3.220

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Continuation of Table 1

Results of radon measurements in wells on the peninsula. Manawi, Y. et al (2023)

Well Code	Radon Bq/L	Well Code	Radon Bq/L
2357	10.500±0.63	5754	15.300±1.910
2534	11.00±2.370	5799	14.500±1.250
2537	10.50±2.370	6055	15.600±0.485
2626	4.870±0.623	6191	18.900±1.040
2709	10.800±1.110	6199	17.200±1.840
2874	37.200±2.860	6555	7.500±0.665
2940	44.00±2.240	7418	8.590±0.999
2990	27.20±1.40	8019	11.100±1.030

The country's territory is traditionally classified as an aseismic region, but seismic events still occur. In particular, on 16/03/2022, an earthquake with a magnitude of 3.2 and a focal depth of 10 km was recorded in the Musay‘īd, Al Wakrah region. And on 27/05/2005, a seismic event with a magnitude of 3.2 was recorded in the southwest of the country, on the border with Saudi Arabia. Episodic seismic events were also recorded in the water area, including near Bahrain with a magnitude of 3.0–3.2. All of the above indicates the presence of a certain seismic potential in this territory. However, its nature still needs to be clarified.

Findings

When analyzing the factual material, especially maps, and diagrams, attention is drawn to the close-to-linear arrangement of anomalous zones with radon content in groundwater. This cannot be explained by geological boundaries between layers or other (geochemical) reasons. According to this work such a pattern of anomalies can only be a consequence of presence the tectonic fault zones, moreover, it’s activity isn’t clear. Also noteworthy is the large amplitude of the measured values of radon volume activity in the selected 48 wells, recorded in the range from 2.71 to 60.70 Bq/l.

Based on the analysis of research data, tectonic fault lines were assumed within the peninsula (Fig. 4). Their location is in good agreement with the fault zones mentioned in the works of Abu-Zeid Mohamed M. (1991) and Jacques LeBlanc (2021). It is possible to confirm a more precise location of fault zones throughout the entire area of the peninsula only with additional large-scale profile (radon) explorations.

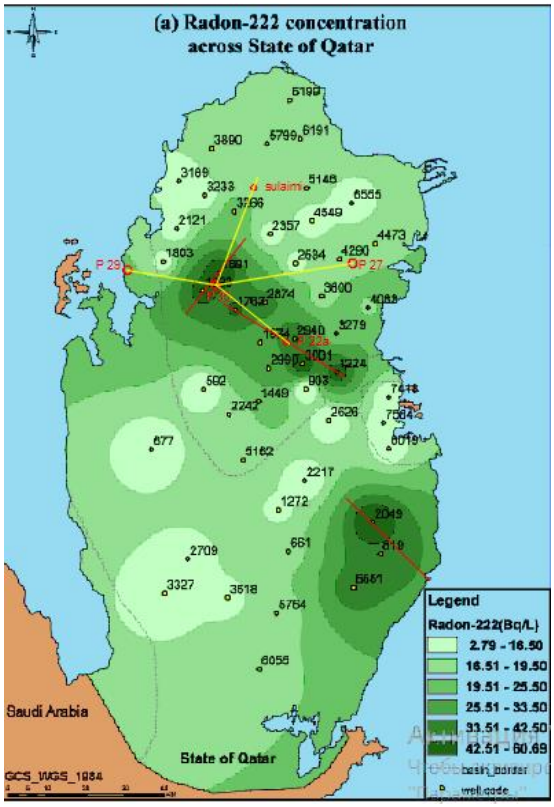

Fig. 4. Profiles through marker wells and lines of possible strikes of tectonic fault zones on the peninsula (highlighted in red). Manawi, Y. et al (2023)

It should be especially noted that the fault zone in the area of wells 2049, 819, and 5551, assumed by radon measurements, is completely absent on the E–W section shown in Fig. 2, 3 in the article by John M. Rivers et al. [15]. This indirectly indicates the wide additional capabilities of the technique.

The authors assessed radon activity in the identified tectonic faults within the Qatar Peninsula using the conducted explorations with using their own methodology, which is given in References to this article. This methodology is a radically revised and expanded earlier idea (Seminsky et al.), initially based only on soil radon measurements. The fundamental difference of the new methodology first introduced in the form of a universal scale, is the possibility of applying it to soil radon and radon in groundwater. And in the latest version of the methodology – with the possibility of evaluating the linear activity of the fault zones themselves. However,

doi: https://doi.org/10.15802/stp2024/316330

the results of radon measurements on the Qatar Peninsula, show a significant spread of values. In relation to these results for calculating the activity of the faults the authors do not use the ratio of max/min measurements for the selected profiles. Instead, it should be used average indicator of the radon measurement results on the wings of the fault zones. These wings are within the proposed profiles between the selected most representative wells with maximum contrast (Table 2).

Table 2

Summary Table of radon activity of tectonic faults on the Qatar Peninsula with the evaluation of possible displacements along faults

Item No.	Measurement results on selected profiles						Average value VAR, Bq/l	KQ	Radon activity level of radon according to KQ	Possible velocity of displacement along faults, mm/year
	Left-wing of the fault		Fault zone		Right-wing of the fault					
	Well No.	VAR, Bq/l	Well No.	VAR, Bq/l	Well No.	VAR, Bq/l				
1	2626	4.87	1224	52.4	4083	18.3	11.59	4.52	medium-active	1–2
2	903	2.71	1224	52.4	7418	8.59	5.65	9.27	active	2–5
3	592	5.57	3001	55.5	3279	20.9	13.23	4.2	medium-active	1–2
4	2242	14.4	3001	55.5	4083	18.3	16.4	3.38	medium-active	1–2
5	592	5.57	2940	44.0	3800	14.5	10.0	4.4	medium-active	1–2
6	592	5.57	1762	45.3	2534	11.0	8.28	5.47	active	2–5
7	592	5.57	1993	49.4	3233	11.0	8.28	6.0	active	2–5
8	1803	11.9	1891	55.8	2357	10.5	10.3	5.41	active	2–5
9	2217	6.9	2049	60.7	8019	11.0	9.0	6.72	active	2–5
10	5551	39.1	2049	60.7	8019	11.0	25.1	2.42	low-active	0–1
11	661	16.5	2049	60.7	8019	11.0	13.8	4.4	medium-active	1–2

Note: VAR – the volumetric activity of radon (VAR)

If we evaluate such an important element of tectonic activity as the nature of the displacements themselves in practical terms of the assumed fault zones and all other things being equal then large values of the KQ index are characteristic of faults and shears compared to upthrusts and thrusts. Although a direct connection between the nature of displacements or the contrast of the near-fault radon anomaly is naturally complicated by the influence of other components of tectonic activity.

The obtained values generally agree well with the developed universal scale. Processing the available data using the universal scale has already allowed us to assess the obtained results and evaluate the radon activity of the assumed fault zones from today's standpoint, suggesting their own interpretation. It should be especially noted that the given sample values (for a total of 48 wells) are too few and for this reason cannot reflect the entire picture on the peninsula. However, an unexpectedly significant spread in the values of the volumetric radon activity in water along several profiles already makes us evaluate the stress state of the soil massif differently than it was previously thought. It is quite difficult to evaluate the seismotectonic situation using other scale indicators due to the lack of public available data on soil radon measurements on the Qatar Peninsula. However, the values obtained during the exploration and their significant differences within a small area already allow us to raise the issue of continuing the work. It is worth highlighting that one of the radon anomalies in the southeast of the peninsula coincides with the area where an earthquake with M = 3.2 was recorded on 16/03/2022. This is unlikely to be accidental and indicates the presence of some tectonic activity in the

doi: https://doi.org/10.15802/stp2024/316330

area of the assumed fault, which requires further study.

In addition to the geological and structural-tectonic components, the study of radon emission from the earth's interior also has a clearly expressed technical aspect. This may fully apply to the project in creating the «Qatar Rail Long Distance» railway network, which will consist of 4 stages with completion by 2030.

Also, a relatively little-studied field is the possible impact of the identified geodynamic structures on welded pipeline seams for various purposes, especially high-pressure oil and gas pipelines. In the specified territory, these may well include the Ras Laffan-Umm Said, Ras Laffan-Mesaieed, and others. This is especially important for Qatar's energy sector. According to many researchers (Selyukov N. I., Ryaboshtan Yu. S. and others), the negative impact of such structures may be reduced to three main factors, namely:

– mechanical-dynamic factor, associated with local fluctuations of the daytime surface of the soil massif;

– gas-chemical factor, associated with an increased release of corrosive gases from fault zones of active geodynamic structures;

– radiation factor.

The latter is the least studied due to the specific effects of alpha particles formed as a result of radon decay in places of its intensive release from the subsurface resources on the corrosive environment, and, above all, on the water of the groundwater aquifer (the so-called radiolysis effect). Hydrogen peroxide, ozone with OH and H_2O_2 radicals formed during water radiolysis are energetic cathodic depolarizers. For the same reason, the radiolysis effect enhances the cathodic process, and, consequently, the corrosion itself, including the metal of pipeline welds when they intersect such structures.

For a high-quality analysis of the current geodynamic situation on the peninsula, the following types of work should be additionally included in the list of possible specialized (read – geophysical) explorations, namely: measuring radon in groundwater in all accessible hydrogeological wells. As well as measuring soil radon in boreholes near the wells being tested. If possible, work should also be carried out on the coastal part of the Gulf. Moreover, sampling is necessary both from the near-bottom layer of seawater and from the layer of bottom sediments at a depth of at least 1 m from the seabed level. The profiles in the aquatic area should be located transverse to the fault zones identified by seismic exploration or assumed based on radon data.

In the future, such explorations may become an integral part of subsurface resource monitoring, including monitoring of modern tectonic movements of the earth's crust. Refusal to conduct such explorations is fraught with the manifestation of negative geotechnical processes and phenomena soon, which may complicate the operation of pipeline systems and other significant facilities that are critical for the state economy. If the proposed additional explorations confirm the detection of active segments of geodynamic structures associated with radon anomalies in certain areas of the peninsula (and, if it is sufficiently justified, near it, including in the territory of neighboring countries), the issue of the advisability of timely adoption of additional technical measures should be considered.

The relative proximity of the exploration area to the western part of the UAE does not exclude the presence of similar geodynamic processes with similar activity there. A certain similarity of their regional geological and possibly tectonic features could be considered. This raises the question of a similar analysis of soil radon and groundwater radon measurements in the western part of the UAE if such took place there. This is unlikely, because of a very small number of monitoring wells given in this part of the country, in contrast to the eastern and, partly, southern ones [20]. This is the more relevant since the largest operating four-unit Barakah NPP in the region is located in this part of the country. If radon explorations for seismotectonic purposes at the Barakah NPP site were not carried out during engineering surveys and subsequent monitoring, this would serve as an additional argument in favor of their immediate implementation. As follows from the International Atomic Energy Agency (IAEA) documents published as early as 2024, the trend toward tightening NPP safety requirements is only gaining strength. The explorations can also be combined with planned works to clarify the engineering and geological conditions for specific NPP buildings and structures. If active segments of geodynamic structures associated with radon anomalies are discovered (during the proposed additional explorations at the NPP site and adjacent territory – for example, to choose a radioactive wastes landfill after the NPP is liquidated), the advisability of taking timely technical measures should be considered.

doi: https://doi.org/10.15802/stp2024/316330

Such explorations may further become an integral part of subsoil monitoring at the NPP site based on radon measurements. The assumed additional explorations will be able to ensure more complete seismic protection of the operating NPP units. And, as a consequence, accident-free operation of the completed NPP buildings and structures in the long term. These explorations may be especially significant in connection with plans to build a second NPP in the UAE [5]. One of the sites is considered to be the area of the first Barakah NPP, but even closer to the borders of Qatar and Saudi Arabia. That is region adjacent directly to the exploration area described in this article.

Originality and practical value

The analysis of the conducted measurements for the volumetric activity of radon in groundwater in the northern and eastern parts of the Qatar Peninsula, although carried out for other (environmental) purposes, confirmed the fundamental possibility of determining the location of both the fault zones themselves and their tectonic activity based on testing the upper (ground) aquifer. The latter even taking into account its openness and susceptibility to the influence of various man-made factors. Along with determining the activity of the identified fault zones, it became possible to indirectly evaluate the nature of the movement of crustal blocks in this territory. And in the future – the intensity of such movements.

It should be noted that in all the specified highly specialized explorations of radon activity of the identified tectonic faults were carried out on the peninsula for the first time. The authors have no information on such explorations in the country and abroad, in particular, in the UAE, Saudi Arabia, Bahrain, Oman, and Iran.

With further improvement of this method, it is possible to use it in seismically active areas, as well as in territories of neighboring countries adjacent to the peninsula, especially if they have facilities that are important for the economy and security, in particular, nuclear power plants, important pipelines, and railways.

Conclusion

Processing of available data using our own universal scale allowed us to give a new evaluation of previously obtained results and determine the radon activity of the identified fault zones.

In addition to determining the activity of the identified fault zones, it became possible to evaluate the intensity of movement of crustal blocks in this area. However, high-precision geodesy methods using space technologies need to confirm the obtained preliminary data. Nevertheless, their importance for all kinds of transport communications of the state is beyond doubt.

For a high-quality analysis of the current geodynamic situation, explorations in this area should be continued. The list of possible specialized (read – geophysical) explorations should additionally include the following types of work, namely: measuring radon in groundwater by the maximum number of available wells for water supply; and measuring soil radon near the wells being tested. With sufficient justification, the work can also be carried out on the coastal part of the water area. But, this will require the use of special equipment and technology.

The relative proximity of the exploration area to the western part of the UAE does not exclude the presence of similar geodynamic processes with similar activity there, considering a certain similarity of their regional geological, and possibly tectonic features. This, in turn, raises the question of a similar analysis of soil radon and radon measurements in groundwater in the western part of the UAE, if such took place there. This is especially relevant since the largest operating four-unit Barakah NPP in the region is located in this part of the country. Another NPP is planned to be built nearby.

Acknowledgments

The authors would like to express special gratitude to Jacques LeBlanc for his assistance in finding materials for this article.

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До питання про наявність радонової активності тектонічних розломів півострова Катар

Мета. У роботі передбачено дати сучасну оцінку радонової активності виявлених тектонічних розломів земної кори на підставі архівних даних із вимірювань радону в підземних водах, виконаних у північній і східній частинах півострова Катар. **Методика.** Подано додаткове розширене обґрунтування застосування в геологічних умовах півострова Катар інноваційної для цих умов методики виявлення ступеня активності тектонічних розломів скельної основи на підставі сторонніх вимірів радону в підземних водах за допомогою власної універсальної оцінної шкали. **Результати.** Сучасний аналіз раніше отриманих результатів вимірювань радону в підземних водах півострова Катар дав змогу припустити орієнтацію напрямків тектонічних розломів у північній і східних його частинах, і додатково виявити ступінь їхньої радонової активності в межах півострова з попередньою оцінкою величини переміщень по розломах. Також було припущено подібне і на прилеглій до півострова території західної частини ОАЕ, де розташована АЕС Барака. Це припущення базується на певній подібності геологічних і тектонічних умов регіону. **Наукова новизна.** Уперше було запропоновано розташування тектонічних розломів у межах північної та східної частин півострова Катар за даними радонометрії, виконаної з іншими цілями, і подано оцінку їхньої радонової активності та величин переміщення по розломах. Це сприяє підвищенню безпеки під час будівництва та експлуатації різних об’єктів, у т. ч. і підвищеного ступеня відповідальності, зокрема, важливих для економіки країни трубопровідних систем і транспортних комунікацій. **Практична значимість.** Запропонована методика може бути використана і в рамках сейсмомоніторингу будівельних майданчиків і на суміжних територіях інших країн, де подібні дослідження раніше не проводили.

Ключові слова: Катар; радонометрія; свердловини; вимірювання радону; тектонічні розломи

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Надійшла до редколегії: 15.08.2024
Прийнята до друку: 17.12.2024

doi: https://doi.org/10.15802/stp2024/316330