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Review and Analysis of the Main Methods for Determining the Activity Rate of Tectonic Faults Based on the Results of Radonometry

Vasily Yuryevich ULYANOV [1*], Vasyl Volodymyrovych BILYK[2], Serdar DİZMAN [3]

[1] Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 49005, Dnipro, Ukraine
[2] Laboratory of Research of Nuclear and Thermal Power Plants, Prydniprovska State Academy of Civil Engineering and Architecture, 49005, Dnipro, Ukraine
[3] Department of Physics, Faculty of Arts and Sciences, Recep Tayyip Erdogan University, 53100, Rize, Türkiye

Sorumlu Yazar/Corresponding Author
E-mail: uluanovvu@gmail.com

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Abstract

The work compares various radiometry methods for accurately mapping fault zones in complex and simple mining and geological conditions. It also examines the conditions required for their application to confidently evaluate the degree of geodynamic activity of the identified tectonic fault zones, including minimizing negative impacts during the construction of various facilities, including linear transport and energy infrastructure. The authors analysed various materials on previously conducted research on this topic to compare approaches to the problem and develop numerical dependencies. In addition, it was evaluated the dependencies obtained by many researchers and their advantages and disadvantages. After thoroughly analysing previously developed methods and numerical dependencies for determining the degree of activity of tectonic faults, the most preferable method was selected from the list based on several criteria. The applicability parameters of the previously proposed numerical scale of fault activity based on radonometry data were clarified. The numerical scale itself was significantly improved. Based on the analysis of existing radonometry methods, the most acceptable method and an improved universal scale for determining the activity of tectonic faults, which is quite suitable for practical purposes, were proposed. The developed universal numerical scale still has no analogies. Radonometry in its various forms can be used to reliably evaluate the degree of geodynamic activity of the identified tectonic fault zones. For this purpose, the corresponding methodology and numerical scale were chosen.

Keywords: Geological structure, Radon, Tectonic fault, Radonometry, Volumetric activity, Contrast ratio

Radonometri Sonuçlarına Dayanarak Tektonik Fayların Aktivite Oranını Belirlemek için Ana Yöntemlerin Gözden Geçirilmesi ve Analizi

Öz

Çalışma, karmaşık ve basit madencilik ve jeolojik koşullarda fay zonlarını doğru bir şekilde haritalamak için çeşitli radyometri yöntemlerini karşılaştırır. Ayrıca, doğrusal ulaşım ve enerji altyapısı da dâhil olmak üzere çeşitli tesislerin inşası sırasında olumsuz etkileri en aza indirmek üzere belirlenen tektonik fay zonlarının jeodinamik aktivite derecesini güvenle değerlendirmek için bunların uygulama koşullarını inceler. Yazarlar, soruna yaklaşımları karşılaştırmak ve sayısal bağımlılıklar geliştirmek için bu konu hakkında daha önce yürütülen araştırmalardaki çeşitli materyalleri analiz ettiler. Ek olarak, birçok araştırmacı tarafından elde edilen bağımlılıklar ve bunların avantajları ve dezavantajları değerlendirilmiştir. Tektonik fayların aktivite derecesini belirlemek için daha önce geliştirilen yöntemler ve sayısal bağımlılıklar iyice analiz edildikten sonra birkaç kritere göre listeden en çok tercih edilen yöntem seçilmiştir. Daha önce önerilen radonometri verilerine dayalı sayısal fay aktivitesi ölçeğinin uygulanabilirlik parametreleri açıklığa kavuşturuldu. Sayısal ölçeğin kendisi önemli ölçüde iyileştirildi. Mevcut radonometri yöntemlerinin analizine dayanarak pratik amaçlar için oldukça uygun olan tektonik fayların aktivitesini belirlemek için en kabul edilebilir yöntem ve iyileştirilmiş bir evrensel ölçek önerildi. Geliştirilen evrensel sayısal ölçeğin hala hiçbir benzeri bulunmamaktadır. Radonometri, çeşitli seçenekleriyle belirlenen tektonik fay zonlarının jeodinamik aktivitesinin derecesini güvenilir bir şekilde değerlendirmek için kullanılabilir. Bu amaçla, karşılık gelen yöntem ve sayısal ölçek seçilmiştir.

Anahtar Kelimeler: Jeolojik yapı, Radon, Tektonik fay, Radonometri, Hacimsel aktivite, Kontrast oran

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1. Introduction

Radon is an unstable noble gas element in the thorium–lead and uranium–lead radioactive series. The most common isotope of radon is 222Rn, which has the longest half-life for radon at 3.82 days. Radon is present in all rock masses because its losses due to emission into the air are quickly replenished by the continuous regeneration of the gas. On average, every second, a ton of rocky material produces up to 50,000 radon atoms. These atoms reach the surface of the Earth either through cracks in the crust or along with groundwater flows. Consequently, the maximum amounts of radon are recorded in the near-ground air layer, while its concentration in the atmosphere decreases with altitude. There are two groups of radon sources associated with rocks:

- Rocks with increased radon compound content – granites, shales, syenites. Sometimes radon-rich areas occupy large territories, creating an elevated radioactive background.
- Radon-bearing tectonic zones with abnormal radon concentration, characterized by distinct linear dimensions. These zones can stretch for hundreds and thousands of kilometers.

A particularly large amount of radon accumulates in such mobile tectonic fault zones located in seismically active regions of the planet. During tectonic activity, the porosity of rocks increases, forming numerous cracks and cavities where radon accumulates. However, if the edges of the faults remain stationary, the fractures are quickly filled with water and dissolved particles of rock, leaving no space for gas accumulation. As is well known, the concentration of radon in soil gas depends on many factors, but mainly on the geological characteristics and tectonic activity of the researched region. Therefore, the absolute values of radon concentration in soil gases and groundwater in various regions may not be the same or even differ significantly. Tectonic activity can be evaluated in various ways, including using radonometry. However, researchers have almost always been interested in soil radon. Although radon in groundwater is also important. The urgent task in the current conditions is to choose the most acceptable and optimal method for evaluating the tectonic activity of faults for practical usage according to radonometry, including both soil radon and radon in groundwater. Discussion of this topic is the purpose of this article.

2. Material and Method

There are many systems for classifying soil radon concentrations while mapping. In particular, in Germany (Kemski et al., 2001) the Rn concentration was divided into 4 categories. At the same time, a three-level scale was used in Hong Kong (Table 1) (Tung et al., 2013).

Numerous research have shown that anomalous radon concentrations are very sensitive to the activity of tectonic faults in the earth's crust (King et al., 1996; Ciotoli et al., 1999; Moussa and El Arabi, 2003). Anomalous radon concentrations in soil gas can be many times higher than the background value, depending on the level of fault activity (Wang et al., 2014). Measurements of radon concentration in soil gas on several faults in different regions of the world show that although the maximum Rn concentration and the background value vary greatly between different faults, the ratio of the maximum Rn concentration to the background value at the same fault or in the same measurement over an area is generally quite constant and close (Richon et al., 2010).

Table 1. Soil radon classification systems for mapping.

Authors of Classifications	Radon Concentration Category (kBq/m³)			
	Low	Medium	Increased	High
Kemski et al. (2001)	<10	10 - 100	100 - 500	>500
Tung et al. (2013)	<10	10 - 100	-	>100

Numerous research have shown that anomalous radon concentrations are very sensitive to the activity of tectonic faults in the earth's crust (King et al., 1996; Ciotoli et al., 1999; Moussa and El Arabi, 2003). Anomalous radon concentrations in soil gas can be many times higher than the background value, depending on the level of fault activity (Wang et al., 2014). Measurements of radon concentration in soil gas on several faults in different regions of the world show that although the maximum Rn concentration and the background value vary greatly between different faults, the ratio of the maximum Rn concentration to the background value at the same fault or in the same measurement over an area is generally quite constant and close (Richon et al., 2010).

In domestic practice, the existence of a numerical relationship between the activity of faults and the intensity of soil radon emissions was mentioned in some works (Boltyrov et al., 2003; Boltyrov and Ostapchuk, 2004; Goloudin and Shabarov, 2008). In particular, the above-mentioned authors classified faults as low-active (less than 1000 Bq/m³) and highly active (more than 2000 Bq/m³) based on the intensity of radon emissions from the subsurface. However, it is very difficult to use the above-mentioned scales in practice, especially for evaluating the activity of fault zones. Due to several reasons, the task of developing a methodology for evaluating geodynamic activity in the formulas and a special numerical scale is extremely urgent, but, in fact, has not yet been finally resolved. At one time, Lunina (2010) proposed the so-called formalized scale based on indirect signs of points assigned according

to the totality, reflecting the relationship between the amount of radon emission from tectonic fault zones and their activity rate (including possible activation) (Lunina, 2010). However, this scale is quite complex and not very convenient for mass application. Ideas for developing a methodology for evaluating geodynamic activity and its numerical scale have repeatedly arisen in domestic practice, but everything was slowed down by the fact that the creation of such a scale required research accompanied by the processing of a large array of statistical data. Moreover, many researchers of this problem generally expressed doubts about the very possibility of creating a technologically complete numerical scale, including due to the lack, until recently, of instrumentation equipment appropriate to the research tasks, especially for long-term continuous (monitoring) measurements. And all this even though the use of radonometry in the complex geodynamic diagnostics of a rock massif did not raise doubts, since it made it possible to optimize the implementation of research and increase the reliability of the results. In particular, considering one of the ways of implementing the idea, the correspondence of geodynamic zoning based on the emanation survey data and geodynamic zoning in line with the GPS measurements of modern geodynamic movements was experimentally established. The radonometry data reflected the entire frequency spectrum of modern geodynamic movements. The dependence of field parameters of the radon emanation on the parameters and mechanism of modern geodynamic activity made it possible to use radonometry in a complex of geodynamic diagnostics and for operational geodynamic zoning. Geodynamic zoning of the rock massif based on the emanation survey made it possible to optimally measure the quantitative parameters of modern geodynamic activity during the research, including using high-precision GPS measurements. It is also obvious considering recent research that to successfully solve this problem, it is necessary to comprehensively use both the characteristics of soil radon and radon in groundwater circulating in fault zones. As noted by many researchers, the characteristics of soil radon, as stated by many researchers, are influenced by many factors that seriously complicate the establishment of stable numerical dependencies. However, the situation with instrumentation for continuous radon monitoring, in particular, in groundwater, has begun to change for the better in recent years (Wang et al., 2020; He et al., 2022). This means that serious progress in researching the problem is possible. Below, the main patterns identified by researchers from different countries in determining the degree of geodynamic activity of tectonic faults in the Earth's crust based on radonometry data are considered and analysed.

2.1. Methodology from the Institute of the Earth Crust of the Siberian Branch of the Russian Academy of Sciences

Employees at the Institute of the Earth Crust of the Siberian Branch of the Russian Academy of Sciences (Irkutsk, Russia) Bobrov (2006) and others offered a patent-protected method for evaluating the activity of fault zones (Ryaboshtan and Takhtamirov, 1979; Bobrov, 2006; Seminsky and Bobrov, 2009; Seminsky and Demberel, 2013). They evaluated the contrast of emanation anomalies using the relative indicator (equation 1).

$$KQ = Q_{max}/Q_{min} \qquad (1)$$

where Q_{max} is the maximum value of the parameter Q in the fault zone, and Q_{min} is the minimum value of the parameter Q in the rocks outside the fault zone. This allowed them, based on extensive field research data in the Transbaikal and Baikal regions, perhaps for the first time, to distinguish five groups of fault zones with the following emanation (radon) activity. In the authors' opinion, the influence zones of faults belonging to the last two groups represent an undeniable hazard in terms of the construction and operation of critical buildings and structures. Furthermore, the use of the radon activity indicator proposed by the authors is preferable compared to using absolute values. However, the lack of a universal numerical scale based on the results of geodynamic research, considering all the combined factors, seriously limits the applicability of this parameter. In addition, these dependencies were initially determined based on measurements of soil radon only. Some Chinese researchers follow a similar approach but their gradation of fault activity is somewhat different, namely (Table 2) (Yang et al., 2018).

2.2. Methodology of the Institute of Geophysics and Geological Sciences from Hanoi

According to the researchers from the Institute of Geophysics and of Geological Sciences (Hanoi, Vietnam), the use of the Semminsky and Demberel (2013) classification led to uncertainties. This is especially true for the results of measurements outside the fault zone: which of these values should be selected and what will be the cost of an error in selecting the minimum values, given the distance from the measurement point to the fault zone? Local researchers from the aforementioned institutes proposed using their indicator instead of the contrast of radon anomalies K_Q - the radon activity index K_{Rn} (Xuan et al., 2017, 2020). This is the ratio of the anomalous Rn value to the background Rn value, which corresponds to the level of fault activity (equation 2).

$$K_{Rn} = \frac{Rn\ anomaly\ value}{Rn\ background\ value} \quad (2)$$

Thus, the radon activity index can be divided into five levels (Table 3).

Table 2. Classification of fault zone activity based on the contrast index of radon anomalies

Authors of Classifications	Activity of Fault Zones by Indicator (*KQ)*				
	Low	**Medium**	**Increased**	**High**	**Super High**
Bobrov, (2006) Seminsky et al. (2014)	KQ≤2	2<KQ≤3	3<KQ≤5	5<KQ≤10	KQ>10
Yang et al. (2018)	KQ < 3	6 > KQ > 3	-	KQ > 6	-

Table 3. Classification of fault zone activity based by radon activity index

Authors of Classifications	Activity of Fault Zones by Radon Activity Index (K_{Rn} / I_{Rn})				
	Low	**Medium**	**Increased**	**High**	**Super High**
Xuan et al. (2017, 2020)	$K_{Rn} \leq 5$	$10 \geq K_{Rn} > 5$	$15 \geq K_{Rn} > 10$	$20 \geq K_{Rn} > 15$	$K_{Rn} > 20$
Liu et al. (2024)	$I_{Rn} < 1,5$	$1,9 > I_{Rn} > 1,5$	-	$I_{Rn} > 1,9$	-

The derived boundary parameters correspond to 5 levels of activity of tectonic fault zones, namely:
$K_{Rn} > 20$; fault with pronounced activity
$20 \geq K_{Rn} > 15$; fault with the clear expression of activity
$15 \geq K_{Rn} > 10$; fault with pronounced activity or the presence of a clearly visible fault zone
$10 \geq K_{Rn} > 5$; fault with the unclear expression of the activity or the presence of a visible fault zone
$K_{Rn} \leq 5$; fault without manifestation of activity.

As an application of this method, Vietnamese scientists have satisfactorily explained the relationship between the activity of existing tectonic faults and radon activity index in the areas of Thac Ba, Song, Thua Tien Hue, Tranh-2 hydropower plant in Ninh Thuan (Vietnam) (Xuan et al., 2020). However, in essence, the indicator derived by Vietnamese researchers is just a slightly modified formula by Seminsky and Demberel (2013).

I_{Rn} as a similar parameter was also used by a Chinese researcher (Liu et al., 2024). Only the I_{Rn} values were divided into three groups representing different levels of fault zone activity. Also, as in the previous case, the absence of a universal numerical scale based on the results of geodynamic research somewhat limits the applicability of this parameter. In addition, these dependencies were initially defined based on measurements of soil radon only.

2.3. Methodology of the Italian Institutes of Geology, Geophysics and Volcanology

According to the researchers of the problem from the Institute of Geology, Ecology and Geoengineering (Rome), the Institute of

Geophysics and Volcanology (Rome), and the Department of Earth Sciences of the University of Padua, the use of the Semminsky and Demberel (2013) classification also needs further development. Local researchers from the aforementioned institutes also proposed using their own indicator - the radon geochemical activity index *RAI* instead of the contrast of radon anomalies K_Q (Benà et al., 2022). This is the ratio of peak Rn values to the background Rn value (equation 3), which corresponds to the level of geochemical activity of the fault and simultaneously characterizes the fracturing of the rock massif.

$$RAI = \frac{Ratio\ of\ peak\ Rn\ values}{Background\ Rn\ value} \quad (3)$$

The calculated *RAI* values were grouped into four classes (Table 4).

Table 4. Classification of fault zone activity based by radon geochemical activity index

Authors of Classifications	Activity of Fault Zones by Radon Geochemical Activity Index (RAI)			
	Low Geochemical Activity	Moderate Geochemical Activity	High Geochemical Activity	Very High Geochemical Activity
Benà et al. (2022)	RAI < 2	2 < RAI < 3	3 < RAI < 6	RAI > 6

The application of this method, according to scientists from these institutes, quite satisfactorily explained the relationship between the activity of existing tectonic faults and the index of geochemical activity of radon in the regions of Northern Italy. However, in essence, the indicator derived by Italian researchers is actually the same slightly modified formula of Seminsky and Demberel (2013). Also, as in the previous case, the lack of a universal numerical scale based on the results of geodynamic research limits the applicability of this parameter. Moreover, these dependencies were determined based on measurements of soil radon only. And the main emphasis was placed on the geochemical component of inactive fault.

2.4. Methodology from the Institute of Mining of the Ural Branch of the Russian Academy of Sciences

The methodology of radonometric studies in geodynamic diagnostics of the Mining Institute of the Ural Branch of the Russian Academy of Sciences (Yekaterinburg) was based on the direct dependence of the values of radon volumetric activity in the soil air of the researched rock massif on the intensity of its modern mobility (Ulyanov, 2017). To eliminate the influence of non-tectonic factors (areal differentiation by diffusion properties of covering deposits, by the material composition of rocks, etc.) on the reliability of the research results during geodynamic zoning using radonmetry, it was proposed to use a normalized value of radon volumetric activity in the soil air. For this purpose, the values of radon volumetric activity obtained as a result of field measurements are grouped according to their belonging to similar areas: – by diffusion properties of covering deposits; – by the material composition of rocks; – by the position of the groundwater level; – by soil moisture saturation of the area, etc. For each measurement point in the group, normalized values of radon volumetric activity are calculated using equation 4.

$$N_i = Q_i / Q_{mean} \quad (4)$$

where N_i is the normalized volumetric radon activity of measurement point i, dimensionless quantity; Q_i is the value of volumetric radon activity in soil air at the measurement point on the profile line, Bq/m^3; Q_{mean} – arithmetic mean value of volumetric radon activity in soil air for a group of measurement points, Bq/m^3.

Normalizing allows for defining the geodynamic component of the radon field formation (Dalatkazin, 2024). In this case, N_i is actually an index of geodynamic activity at the measurement point, which allows for ranking the studied rock massif according to the degree of modern geodynamic activity. Using the interpolation method, a map of the distribution of normalized values of radon volume activity in the soil air of the studied area is constructed. The interpretation of the radon measurement results for geodynamic zoning is carried out according to the principle of the direct dependence between the radon field formation and the intensity distribution of current geodynamics. However, as in previous cases, the lack of a universal numerical scale based on the results of geodynamic research also limits the applicability of this parameter. Also, the derived dependencies were determined based on measurements of only soil radon.

2.5. Methodology of the Educational and Scientific Institute "Prydniprovska State Academy of Civil Engineering and Architecture"

The dependencies previously developed by the Institute of the Earth's Crust from Irkutsk, under certain assumptions, may well be valid for the volumetric activity of radon (VAR) in groundwater. Having brought together all the available results of similar research in different countries, considering their advantages and disadvantages, the Educational and Scientific Institute "Prydniprovska State Academy of Civil Engineering and Architecture" (Dnipro, Ukraine) proposed its method for determining the activity of faults based on radonometry data, equipped with a specially developed single universal numerical scale. The scale also necessarily took into account the contrast of emanation (radon) anomalies (Sedin et al., 2015). For ease of applicability of the scale, its original version was supplemented with a parameter proposed at one time by Ryaboshtan (1975). Such a parameter was the so-called de-emanation coefficient K_d, which is one of the basic parameters of the method of structural-geodynamic mapping (Ryaboshtan, 1975; Selyukov and Stigneeva, 2010). For a more confident sorting of the identified anomalies during field work, the de-emanation indicator K_d is used - an indicator that characterizes the degree of change in the radon concentration after pumping the well, is determined by the formula (equation 5).

$$K_d = N_{01} / N_0 \quad (5)$$

where N_{01} is OAR after pumping and N_0 is OAR before pumping (OAR - volumetric activity of radon in water). In the final version, the authors of this article supplemented their own unified universal scale of this method with another parameter of possible linear displacement of fault zone elements (Table 5).

The condition for the applicability of the specified scale is the absence of any significant uranium-thorium mineralization of rocks in the fault zone (which can significantly distort the results of the research), significant so-called hydro geochemical barriers for the radium sedimentation, as well as the integrated approach in the handling of work. This is

Table 5. Scale of activity of tectonic faults according to the intensity of radon release (new)

Defined Base Parameters	Degree of Fault Activity					Reference
	Inactive	Low Active	Medium active	Active	Highly Active	
Intensity of radon release from fault zones, Bq/m³ (soil radon)	< 1500	1500- 8000	8000 –35000	35000-10000	>100000	Sedin et al. (2015)
Intensity of radon release from fault zones, Bq/l (radon in groundwater)	< 1	1– 10	10 –50	50-100	100-185	Sedin et al. (2015)
Contrast ratio of emanation and water anomalies *KQ*	KQ≤2	2<KQ≤3	3<KQ≤5	5<KQ≤10	KQ>10	Seminsky and Demberel, (2013)
De-emanation coefficient for water anomalies Kd (radon in groundwater)	Kd < 1	Kd < 1	Kd = 1	Kd > 1	Kd > 1	Ryaboshtan and Takhtamirov, (1979)
Displacement rate along the fault, mm/year	0	0-1	1-2	2-5	> 5	Ulyanov and Bilyk, (2024)

especially true for radon in water, since according to the domestic classification, waters with a radon content of more than 185 Bq/L are already classified as very weak radon waters. And, against this background, identifying the essence of the "tectonic" component for evaluating activity is already becoming a difficult task. With the compatibility of the values of all the basic parameters of the scale, established as a result of the entire complex of works, the reliability of determining the degree of activity of the faults will be significantly higher. Otherwise, additional clarifying research on individual parameters will be necessary, but even in this form, the specified revised and improved scale can be used for evaluative judgments.

The quality of the data obtained when implementing the methodology directly depends on the correct division of the site of the upcoming work into profiles. When choosing the location of radon profiles, one should consider the geomorphology, geology, and tectonics of the site. It is desirable to arrange the profiles within one geomorphological element or one tectonic structure. When calculating the parameters, it is necessary to take into consideration the possible fragmentation of radon activity values even within one fault zone, as well as their variability over time. The same applies to the choice of maximum and minimum radon activity values within the profile, as well as the remoteness of the points of minimum values from the fault zone, depending on the test step on the profile and the necessary thickening of the profiles themselves. It should also be considered that soil radon, as a rule, spreads beyond tectonic faults due to increased fracturing of the upper horizons of the cover, especially sedimentary rocks. In connection with this circumstance, the width of the radon anomaly in such rocks almost always exceeds the width of the fault itself. Although the zone of dynamic influence of faults is a rather general concept, including all types of fractured zones, but approximately, the width of the zone of dynamic influence for local and in-situ faults can still be estimated using the formula (equation 6) given in the work Kocharyan and Batukhtin (2018), namely:

$$F^w = kL \quad (6)$$

where L is the fault length, km; k is a coefficient depending on the scale and type of rock fracturing, the range of which is k from 0.1 to 0.2 for local and regional faults, respectively. Some researchers point too much smaller values of k, up to 10^{-4} (Sherman et al., 1983).

If the fault zone is represented by multiple parallel or subparallel disturbances, then both minimum and maximum values are possible within this zone, and also their alternation, which often complicates the interpretation. Moreover, data averaging in this case does not contribute to achieving the correct result. (*Note: However, it is not worthwhile to completely exclude data averaging. In some cases, in particularly difficult conditions and with a sharp difference between the maximum and minimum values, data averaging of minimum values may be justified*). It is also necessary to take into account the kinematics of faults (normal fault, shear, thrust, etc.), which have their own characteristics in the so-called hanging and lowered walls, etc. (Sun et al., 2018). In an extra complicated case, for the precise mapping of sites with different activities, it is possible to research the profile along with the fault itself. A special case is the determination of radon activity at the intersection of fault zones, especially of different ranks. In this case, to exclude errors in the selection of profiles, it is necessary to use the location of sampling points along a circle with the centre at the intersection point of the faults. The radius of the circle and the sampling step are selected based on the specific conditions of the tectonic structure and geomorphology of the research area. If necessary, there may be several circles with sampling points.

When using existing water points to determine radon in water, their location relative to the fault zone should be considered when selecting transverse profiles, preferably intersecting the fault zone at a right angle (as in the case of soil radon, if there are no converging fault zones). The latter is provided that the fault zone is sufficiently well expressed in the relief, or its position is precisely defined. Preference during testing should be given to continuously operating or free-flowing wells, as well as ascending springs, including thermal ones. It is also necessary to consider the technical condition of artificial water points. The location of wells (as well as testing points for soil radon) on the profile should be as symmetrical as possible, otherwise (one central well in the fault zone and only one on the flank) may somewhat distort the results. However, this condition is often difficult to implement in practice, unlike soil radon measurements. Although, in the case of soil radon, one-sided testing (only to the left or right of the fault zone) should be avoided in every possible way (if there are no restrictions on the terrain and accessibility). Distortion of the results is also possible if the tested water points within even one profile are very different in technical or mining-geological characteristics. And there are no other water points, or the possibility of drilling new ones is very difficult.

Visualization of the results obtained can be different. However, it should be quite descriptive and useful for practical application. There are enough examples of the design of research results (González-díez et al., 2009; Manawi et al., 2023; Faryabi et al., 2024). This is especially important for the correct and justified selection of areas of background (flank) parameter values. To avoid errors in choosing the minimum values and distortion of the radon activity indicator (contrast coefficient K_Q), the flank points should be from approximately the same range of gradations of the testing results, for which a special colour map is compiled based on the results of testing the profiles (Mehrabi et al., 2021). If the values of all basic parameters established as a result of the entire complex of works are compatible, the reliability of determining the degree of fault activity will be significantly higher. Otherwise, additional clarifying research on individual parameters will be necessary; however, even in this form, the specified scale can be used.

3. Result and Discussions

After analysing the dependencies developed in various countries, the most suitable of them for determining the degree of activity of tectonic faults are given in Table 6.

As can be seen, in the opinion of the authors of this article, only the method of the Educational and Scientific Institute "Prydneprovska State Academy of Civil Engineering and Architecture" most fully meets the criteria of universality, including individual elements of the methods from the Institute of the Earth's Crust in Irkutsk and "Coal Geology" from Donetsk. The combined method's universality and compatibility with existing/promising systems for measuring crustal fault displacements are particularly notable. The universal scale as a component of the groundwater radonometry methodology was first used when analyzing materials on several territories, particularly on the tectonics of one of the nuclear power plant sites in Türkiye (Sedin and Ulyanov, 2019) and individual sections of the peninsula in Qatar (Ulyanov and Bilyk, 2024).

3.1. Originality and practical value

Radonometry in its various forms can be quite effectively applied for a more or less reliable evaluation of the degree of geodynamic activity of the identified tectonic fault zones. Including those located under a thick layer of loose-cover sediments. For this purpose, the corresponding dependencies and a universal numerical scale for one of them were developed. Of all the considered variants of the methods, it is the proposed method that is the most efficient and has the potential for further development, given the introduction of the linear displacement parameter. The presence of a numerically improved and completed scale reveals that this method has a significant advantage over the previously discussed methods.

4. Conclusions

Radonometry in its various variants can be used to reliably evaluate the degree of geodynamic activity of the identified tectonic fault zones. This includes faults beneath thick layers of loose cover deposits. For this purpose, the corresponding methods and a universal numerical scale for one of them were developed. The article examines the main atterns identified by domestic and foreign researchers in determining the degree of geodynamic activity of tectonic faults of the earth's crust using radonometry data and briefly discusses the features of applying one of them.

After a thorough analysis of the previously developed dependencies for determining the degree of activity of tectonic faults, the most

Table 6. Determining the degree of activity of tectonic faults according to radonometry data (Basic methods)

Names of scientific institutions	Educational and Scientific Institute "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine
Surnames developers	Ulyanov and others
Type of radon	Soil radon, groundwater radon
Defined parameter	Relative indicator of radon activity De-emanation coefficient
Designation	K_Q K_d
The essence of the proposals	Relative indicator of radon activity according to the measurement profile: K_Q - the maximum ratio Rn concentration (Q_{max}) to the minimum Rn concentration outside the fault zone (Q_{min}) to classify fault activity*
Categories of activity tectonic faults according to radonometry data	Fault activity is characterized by radon activity levels as follows** Ultra-high ($K_Q > 10$), High ($10 > K_Q > 5$), Elevated ($5 > K_Q > 3$), Medium ($3>K_Q>2$), Low ($K_Q < 2$)
The presence of a generalized numerical scale Measurements geodynamic activity according to radonometry	Developed

* For a more confident sorting of the identified anomalies during field work, the de-emanation indicator K_d is used - an indicator that characterizes the degree of change in the radon concentration after pumping the well, is determined by the formula:

$Kd = N_{01}/N_0$,

where N_{01} is OAR after pumping and N_0 is OAR before pumping (OAR is volumetric activity of radon)

** Depending on the value of K_d:

$K_d < 1$ - the ratio is typical for screening anomalies, i.e., for soil conditions with difficult gas exchange.

$K_d = 1$ - ratio characteristic of tectonic disturbances, cracks in a quiet state.

$K_d > 1$ - characterizes emanation anomalies, usually occurs over activated areas.

preferable of them were selected according to several criteria. It is the proposed method that is currently the most preferable but still needs more large-scale verification research in areas with active tectonics, accompanied by seismic events of various ranks. Such areas, in particular, may well include the strip along the route of the projected Eastern Siberia - Mongolia - China gas pipeline within the territory of Mongolia and China, Western Siberia - Kazakhstan - China, Central Asia - China, the railway route to Sakhalin Island, nuclear power plant sites in Türkiye (Sinop), Egypt (El Dabaa), Bushehr (Iran), Barakah (UAE) and hydroelectric power station on the Nile (Ethiopia), etc. As well as other large infrastructure facilities. It is also not worth excluding the possibility of conducting similar research in aseismic regions, as well as on the shelf.

The realization of radonometry in the surface layer of the atmosphere and in permafrost regions for the stated purposes is a separate topic that has been little studied. But for conducting such research, especially in the Arctic and Antarctic regions, the above-described methodology needs to be rethought and created anew. The instrumentation base is also subject to improvement.

Author Contributions

Ulyanov, V.Y: Methodology, investigation, numerical analysis, software, data processing; writing-original draft. Bilyk, V.V: Supervision, methodology, data processing, writing-original draft and editing. Dizman, S: Data processing, writing-original draft and editing.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Disclaimer

The expressed opinions and thoughts reflect only the authors' views and do not represent the views of their affiliation institutions. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; in the decision to publish the results

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