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FEATURES IN THE ORGANIZATION AND IMPLEMENTATION OF RADONOMETRY FOR SEISMOTECTONIC PURPOSES AT TRANSPORT AND ENERGY INFRASTRUCTURE CONSTRUCTION SITES IN THE PERMAFROST ZONE

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Abstract. ***Problem statement.*** The paper analyzes the few explorations performed in this field and the conclusions obtained during the research. In reality, a comprehensive study of gas-saturated frozen soils has not been carried out at present. This has not been done either in geocryology as a whole, or within its specific lines: mechanics of frozen soils, structural geocryology, dynamic geocryology, and especially cryo-seismotectonics. There are only individual works that fragmentarily consider specific issues related to the gas saturation of frozen rocks, mainly in areas of gas- and oil production. But in modern conditions, this position should be radically revised, since a practical need has been formed to study the structure, properties, and seismotectonic processes in the zone of permafrost soils. In recent years, specialized emanation (including radon) research, conducted both in combination with some shallow geophysical work (electrical tomography, microseismic sounding, high-precision gamma spectrometry) and independently, have received some development in the countries of the Arctic (Canada, the US state of Alaska, Greenland, Spitsbergen, northern Eurasia) and Antarctic zones, as well as some internal regions of Asia (the Himalayas, Mongolia). This was because the gas component is an important feature of permafrost. The goals of such work were initially both ecology (especially after it was established that after the thawing of frozen soils in certain areas, the radon emanation increased tens of times) and geological exploration. ***Purpose of the article.*** Modern evaluation of organizational and technical methods for detecting radon activity of identified tectonic faults of the earth's crust in the permafrost zone. ***Conclusions and results.*** The authors propose a refinement of the existing methodology for detecting both faults themselves in the permafrost zone and evaluating their tectonic activity. Additionally, for confident sorting of radon anomalies and identifying the parameters of fault zones necessary to define their tectonic activity, it is recommended to introduce a special parameter – a coefficient for frozen soils that characterizes the permeability of the medium (the degree of radon emanation) after permafrost thawing. A modern analysis of previously completed works allowed us to suggest focusing further efforts on conducting radonometry in range zones of permafrost soil, studying the existing instrumentation and technical base for solving target problems and finding ways to improve it.

Keywords: *permafrost; radonometry; boreholes; radon measurements; tectonic faults*

ОСОБЛИВОСТІ ОРГАНІЗАЦІЇ ТА ВИКОНАННЯ РАДОНОМЕТРІЇ ДЛЯ СЕЙСМОТЕКТОНІЧНИХ ЦІЛЕЙ НА МАЙДАНЧИКАХ БУДІВНИЦТВА ТРАНСПОРТНОЇ ТА ЕНЕРГЕТИЧНОЇ ІНФРАСТРУКТУРИ В ЗОНІ ВІЧНОЇ МЕРЗЛОТИ

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Анотація. ***Постановка проблеми.*** У роботі проаналізовано деякі виконані у цій галузі дослідження, і навіть отримані висновки під час досліджень. Слід зауважити, що комплексного вивчення газонасичених мерзлих ґрунтів досі не здійснювалося. Цим питанням не займалися ні в геокріології загалом, ні в її окремих напрямках: механіці мерзлих ґрунтів, структурній та динамічній геокріології. Існують лише поодинокі праці, які розглядають окремі аспекти газонасичення мерзлих порід, переважно в районах газо- і нафтовидобутку. Однак у сучасних умовах цю позицію слід докорінно переглянути, адже сформувалася нагальна практична потреба у вивченні структури, властивостей та сейсмотектонічних процесів у зоні вічномерзлих ґрунтів. В останні роки спеціалізовані дослідження еманації (включаючи радон), що проводяться як у поєднанні з деякими неглибокими геофізичними роботами (електрична томографія, мікросейсмічні зондування, високоточна гамма-спектрометрія), так і самостійно отримали певний розвиток у країнах Арктичної (Канада, штат Аляска США, Гренландія, Шпіцберген, північна Євразія) та Антарктичної зон, а також у деяких внутрішніх регіонах Азії (Гімалаї, Монголія). Це пояснювалося тим, що газова складова є важливою особливістю вічної мерзлоти. Цілями таких робіт спочатку були як екологія (особливо після того, як було встановлено, що після відтавання мерзлих ґрунтів у певних районах еманація радону збільшувалася в десятки разів), так і геологорозвідувальні роботи. ***Мета статті***. Метою статті є сучасна оцінка організаційних та технічних способів виявлення радонової активності виявлених тектонічних розломів земної кори в зоні поширення вічномерзлих ґрунтів. ***Висновки.*** Запропоновано уточнення існуючої методики виявлення як самих розломів у зоні вічної мерзлоти, так і оцінки їх тектонічної активності. Додатково, для впевненого розбракування радонових аномалій та виділення параметрів розломних зон, необхідних для визначення їхньої тектонічної активності, рекомендовано ввести спеціальний параметр – коефіцієнт для мерзлих ґрунтів, що характеризує проникність середовища (ступінь радоновиділення) після відтавання мерзлоти. Сучасний аналіз раніше виконаних робіт дозволив припустити орієнтацію подальших зусиль на проведення радонометрії у зонах поширення вічно мерзлих ґрунтів. А також вивчення наявної приладової та технічної бази для вирішення цільових завдань та шляхів її вдосконалення.

Ключові слова: *вічна мерзлота; радонометрія; свердловини; вимірювання радону; тектонічні розломи*

Introduction. In reality, a comprehensive study of gas-saturated frozen soils has not been carried out at present. This has not been done either in geocryology as a whole, or within its specific lines: mechanics of frozen soils, structural geocryology, dynamic geocryology, and especially cryo-seismotectonics. There are only individual works that fragmentarily consider specific issues related to the gas saturation of frozen rocks, mainly in areas of gas- and oil production. But in modern conditions, this position should be radically revised, since a practical need has been formed to study the structure, properties, and seismotectonic processes in the zone of permafrost soils.

In recent years, specialized emanation (including radon) research, conducted both in combination with some shallow geophysical work (electrical tomography, microseismic sounding, high-precision gamma spectrometry) and independently, have received some development in the countries of the Arctic (Canada, the US state of Alaska, Greenland, Spitsbergen, northern Eurasia) and Antarctic zones, as well as some internal regions of Asia (the Himalayas, Mongolia). This was because the gas component is an important feature of permafrost. The goals of such work were initially both ecology (especially after it was established that after the thawing of frozen soils in certain areas, the radon emanation increased tens of times) and geological exploration [1–6; 11].

The latter was conducted primarily in areas of kimberlite occurrence and oil and gas fields, including those located on the shelf of the northern seas. The scope of research work has expanded significantly with the repeated placement of energy facilities in some of these zones, and with plans to develop transport infrastructure, including railways. An example is the railways in the Himalayas. However, all the work performed was of a point and experimental nature. In addition, they were usually carried out in Summer and mainly on loose soils of the upper horizons. But at present, specialized surveys are in demand at sites in the northern zone, including radonometry for seismotectonic purposes, namely, determining the activity of identified or hidden tectonic faults. Which could not be reliably identified by traditional methods of engineering geophysics in the permafrost zone. All this requires a completely different approach, as well as an off-season mode of work, and on all types of permafrost soils. This is the purpose of this work.

The purpose of the article. Modern evaluation of organizational and technical methods for detecting radon activity of identified tectonic faults of the earth's crust in the permafrost zone.

Methodology and analysis of previously completed work. As mentioned above, the study of gas emission from frozen soils is a poorly studied branch of geocryology. This applies even more to the radonometry in frozen soils. The following two types of research carried out both in natural undisturbed natural and artificially created conditions, are known and described in the scientific literature.

In the first case, the works were carried out along profiles in Summer on one of the kimberlite pipes in the northern region to detect and trace fault zones when placing equipment (radon radiometers, the “Kamera-01” type) in the upper seasonally thawed layer of permafrost soils. The results of 2-day measurements were processed following the experience of researching the radon activity of Mongolian faults [Demberel, 2013]. To correct the results, this research was duplicated by electrical resistivity tomography. The results showed the possibility of detecting fault zones and their structure within the field.

In the second case, the research was also carried out in the northern region, but outside the permafrost soil zone for 5 months to measure the gradual diffusion of radon-222 during the thawing of artificially recreated frozen soil. A mixture of red clay containing a high content of 226Ra filled the bottom of a 200-liter barrel containing a radon source. The barrel itself was buried at a depth of 1.6 m (e. g., the radium source zone), then covered with natural soil, filled with water, and frozen in situ during the winter. Radon measurements were carried out from the soil surface above the container (a disturbed soil layer) and in a background location nearby (an undisturbed soil layer). The experimental results showed a stable relationship between radon flux density and soil temperature profiles at different depths.

Measurements of radon flux density were performed using a radon radiometer by a standard technique.

As can be seen from the conditions of the field experiments, in the first case the measurements were carried out over 2 days of summer time, actually in the near-surface conditions of the seasonally thawed permafrost layer. In the second case, to conduct the research, it was necessary to carry out preliminary volumetric excavation work to place the emanation source, which is not possible in all types of soil, especially in Winter and in the permafrost zone. It is clear that such experiments will be very difficult for large-scale surveys. The duration of the experiment itself in this equipment configuration is also significant, and the work to support the experiment is very labor-intensive and costly. In addition, parallel standard geophysical explorations may be required to confirm the results.

Apart from field observations, the problem of radon emission from frozen soils was also studied using modeling methods. In particular, at the University of Leeds, Paul Grover and his colleague modeled the formation of radon gas, its distribution through soil, permafrost, and typical buildings, including those with underground and above-ground basements, and also those built on piles, using the finite element method [7]. They also found that permafrost acts as a protective barrier for radon gas, reducing emanation on the surface to one-tenth of the background level. But below the permafrost layer, the radon concentration increases up to 12 times. Moreover, this was noted over a wide range of depths.

The obtained values were likely averaged and estimated since radon emission from the subsurface depends on seismotectonics and can vary significantly in different sites. Therefore, the same article indicated that the modeling results must necessarily be confirmed by fieldwork. However, information about the implementation of such work and its results is unknown. In any case, this only indirectly confirms both the need for special verification field work on permafrost soils and the complexity of their high-quality implementation.

Findings. In the context of the target task, it seems necessary to amend the standard methodology for conducting radonometry at the sites of future railways, main pipelines, and energy facilities to identify both hidden or obvious fault zones themselves and determine their possible activity [8; 9]. The basis of the expanded methodology is the staged measurements of the volumetric activity of radon in permafrost soils in special wells. Moreover, when conducting research, the season of the year should be taken into account. During periods of negative temperatures, the first (initial) stage is immediately after the completion of well drilling. The second stage is after forced heating of the shaft by already completed drilling and a settled well (naturally, with the stability of its walls, for example, in rocky or large-debris soils).

Conducting research in this mode is due, among other things, to the inevitable processes of permafrost thawing in the foundations of future transport and energy facilities, accompanied by the release of radon. Also, as a consequence, there is a possible change in the properties of soils, including rocky ones. In this case, the volumetric activity of radon is defined both in the soil air (in the wellbore) and in the liquid phase (in its presence during thermal action on the well walls when opening, for example, in highly icy soils). During positive temperatures, the stage of thermal heating in the wellbores can be excluded. To obtain comparative background values, it is possible to determine the volumetric activity of radon from the seasonally thawed layer near the drilled wells in a favorable season of the year. The issue of radon release from the so-called cryo-pegs, in the case of their opening by the well, should also be worked out, but at later stages of research.

As the practice of laboratory research on the analysis of gas release from monoliths of frozen soils shows, the process itself begins even after their insignificant heating. But for some types of soils (usually sandy-clayey) after heating to -2^{o} C, gas emission usually decreases sharply, which can be a kind of temperature limit of the wellbore heating function. It is noted that at such a limited temperature, the soil usually remains frozen, and therefore the stability of the walls of such wells can be fully ensured. In the case of obtaining high-quality monoliths of frozen soils from non-rocky monolithic or their highly cracked varieties during wells drilling, their processing should also be provided.

The choice of boundary conditions can be significantly affected by the permitted operating mode of the existing target instrumentation for radonometry. For example, the limiting temperature conditions for the operation of the Alfarad+ radon radiometer from "NTM-Protection" Company are stated by the manufacturer to be no lower than +1° C, for the SRS-05 seismic radon station – no lower than +5° C, and for the Kamera-01 in active sorption mode no lower than 0° C.

The lower temperature limit of measurements for the widely known RAD-7 radon radiometer from DURRIDGE Company, Inc. (USA) is also 0° C. For comparison, the lower limit of the exploitability for various versions of the well-known device "AlphaGUARD" (Germany) is declared by the manufacturer to be –10 ºC. The lower limit of operation of radon radiometers Radon Scout PMT and RTM2200 from the company "SARAD" (Germany) is defined even at –20 ºC. The first of them is created specifically for work in field conditions and is equipped with a Lucas camera, and the second for work in low-temperature conditions is equipped with a special heat-protective casing in an external aluminum case (see Fig. 1). The RTM2200 system itself is equipped with heating, an electric dehumidifier, and protection against water suction.

But for Arctic, Antarctic, and high-altitude conditions, these functions on existing equipment should be significantly enhanced, considering the introduction of forced thermal heating of the well in permafrost to release radon into the measurement methodology. Moreover, it is still very difficult to find information in scientific periodicals on year-round radonometry in-situ in the northern latitudes. Thus, all of the above raises, in particular, the question of either modifying the existing equipment to reduce the lower temperature threshold for normal operation or ensuring its operability in low-temperature conditions by other organizational or technical measures.

Fig.1. Thermal protection housing of the RTM2200 radon radiometer in an external aluminium casing. (Published with the kind permission of SARAD GmbH)

A separate issue requiring additional engineering study is the technology of drilling wells in permafrost for radonometry related to determining their depths. Also, methods for sealing wellheads to ensure high-quality radon measurements in the wellbore both directly during drilling and after its completion, and in the case of experiments in wells that have already settled. In any case, the depth of such wells should be greater than the thickness of the seasonally thawed layer and reach the layer of constant temperatures. Considering the possible placement of thermal equipment in the wellbore, its optimal diameter should be at least 168–273 mm. When drilling shallow wells in large-debris soils, common in the northern regions and especially in Northeast Asia, the most appropriate method is to use rotary drilling with a shortened core barrel with insert bits. For wells with a diameter of 219 and 273 mm – a barrel with bar teeth, once created by L.S. Amaryan for the LPG-42 rotary-vane hydraulic pressure meter (see Fig. 2) [10].

Heating the wellbore can be carried out either by electric heating elements from a portable gasoline electric generator or by exhaust gases from the engine of the drilling rig or the portable electric generator itself after they are re-equipped with the necessary fittings. Air temperature in the wellbore is measured by standard portable temperature sensors or thermal analyzers (pyrometers).

When carrying out work above the wellhead in unfavorable periods of the year, a quick-release frame multilayer tilt-covered tent with the necessary equipment to ensure the production process, life support (heater), and fire safety can be mounted.

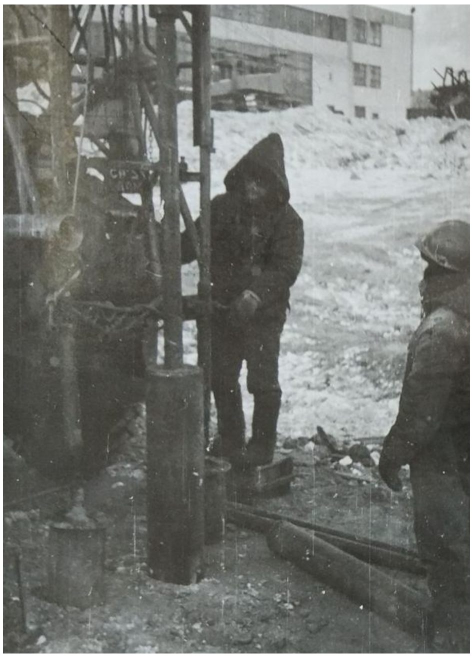

Fig. 2. Shortened core barrel with a diameter of 273 mm (Ulyanov, 2019, 2021)

Originality and Practical value. The proposed refinement of the existing methodology will help to identify both the faults themselves in the zone of ever-frozen subsoil and to evaluate their tectonic activity.

Additionally, for the confident sorting of radon anomalies and the identification of fault zone parameters necessary to determine their tectonic activity, it is recommended to introduce some changes to the standard radonmetry methodology. It is envisaged to introduce a special parameter – a coefficient for frozen soils that characterizes the permeability of the medium (the degree of radon emission) after permafrost thawing – (K_{pm}), determined by the formula:

K_{pm} = volumetric radon activity for frozen soils / the same for thawed soils.

This coefficient can characterize both the permafrost itself (including its ice content) and the physical properties of rocks resulting from its tectonic features in the study area. And also, indirectly contributes to the climatic paleoreconstruction of nature, including paleotectonic conditions of sites of future transport and energy facilities.

Conclusion

This paper highlights some practical and methodological issues in organizing and conducting a completely new direction of radonometry – its implementation at the sites of transport and energy facilities being designed or under construction in the permafrost zone. In particular, the methods of equipping observation points on profiles, possible depths and diameters of wells, as well as the designs of wells and drilling tools themselves are determined.

Additionally, to confidently sort radon anomalies and identify the parameters of fault zones necessary for determining their tectonic activity, it is recommended to introduce a special parameter into the standard radiometry methodology – a coefficient for permafrost soils, characterizing the environment's permeability (the degree of radon emission -Kpm) after forced thawing of permafrost. This parameter can also be used for environmental purposes.

Modifying the existing instrumentation for work in low-temperature conditions is also necessary.

REFERENCES

1. Salzano R., Pasini A., Ianniello A., Mazzola M., Traversi R. and Udisti R. High time-resolved radon progeny measurements in the Arctic region (Svalbard islands, Norway) : results and potentialities. Atmos. Chem. Phys. Vol. 18, 2018, pp. 6959–6969.
2. Farquharson L.M., Romanovsky V.E., Cable W.L, Walker D.A., Kokelj S.V. and Nicolsky D. Climate Change Drives Widespread and Rapid Thermokarst Development in Very Cold Permafrost in the Canadian High Arctic. Geophysical Research Letters. 2019, no. 46, p. 12.
3. Ji M., Kong W., Liang C., Zhou T., Jia H. and Dong X. Permafrost thawing exhibits a greater influence on bacterial richness and community structure than permafrost age in Arctic permafrost soils. Cryosphere. 2020, no. 14 (11), pp. 3907–3916.

4. Shengrong Zhang, Doudou Jin, Huijun Jin, Chunhai Li, Hu Zhang, Xiaoyin Jin and Jian Cui. Potential radon risk in permafrost regions of the Northern Hemisphere under climate change : a review. Earth-Science Reviews. Vol. 250, March 2024, p. 104684.

5. Chuanlei Liu, Jing Chen, Weihua Zhang and Kurt Ungar. Outdoor Radon Dose Rate in Canada's Arctic amid Climate Change. Environ Sci Technol. 2024, Jul 2, no. 58 (26).

6. Seminsky K.Zh. and Demberel S. The first estimations of soil radon activity near faults in Central Mongolia. Radiation Measurements. 2013, vol. 49, pp. 19–34.

7. Glover P.W.J. and Blouin M. Increased radon exposure from thawing ofpermafrost due to climate change. Earth'sFuture, 2022, p. 10.

8. Syedin V.L., Bausk Ye.A., Ulyanov V.Yu. and Bikus K.M. *Shkala ocinyuvannya akttivnosti tektonichniz rozlomiv zemnoyi kori za intensivnistyu radonovidilennya – zastosuvannya dlya obyiektiv AES* [Scale for assessing the activity of tectonic faults in the earth's crust by the intensity of radon release – application to nuclear power plant facilities]. *Osnovi i fundamenti : mizhvidom. nauk.-tehn. zb. Kiyiv. nac. un-t bud-va i arhit.* [Fundamentals and foundations : interdisciplinary scientific and technical collection]. Kyiv : National University of Construction and Architecture, 2015, no. 37, pp. 52–63. (in Ukrainian).

9. Kovba V.V., Ulyanov V.Yu. and Safronova V.S. *Osoblivosti provedennya radonometriyi z metoyu doslidzhennya sejsmotektoniki na majdanchikah AES u zoni vichnoyi merzloti* [Features of conducting radonometry for the purpose of studying seismotectonics at nuclear power plant sites in the permafrost zone]. *Bezpeka zhittyediyalnosti v HHI stolitti : tezi dopov. X Mizhnarodnoyi naukovo-praktichnoyi konferenciyi (21–22 lystopada 2024)* [Life safety in the 21st century : abstracts of the report of the X International Scientific and Practical Conference (November 21–22, 2024)]. Dnipro : USUST, ESI PSACEA, 2024, 109 p. (in Ukrainian).

10. Ulyanov V.Yu. *Shlyahi pidvishennya efektivnosti termopresiometriyi* [Ways to increase the efficiency of thermopressiometry]. *Nauka ta progres transportu. Visnik Dnipropetrovskogo nacionalnogo universitetu zaliznichnogo transportu* [Science and Progress of Transport. Bulletin of the Dnipropetrovsk National University of Railway Transport]. 2021, no. 2 (92), pp 84–91. (in Ukrainian).

11. Ye Yongjun, Zong Yifan, Li Mengyi and Song Bangzhi. Free radon production from uranium tailings under frozen and non-frozen conditions. Journal of Radioanalytical and Nuclear Chemistry. 2023, vol. 334, iss. 3, pp. 2195–2202.

СПИСОК ВИКОРИСТАНИХ ДЖЕРЕЛ

1. Salzano R., Pasini A., Ianniello A., Mazzola M., Traversi R. and Udisti R. High time-resolved radon progeny measurements in the Arctic region (Svalbard islands, Norway) : results and potentialities. Atmos. Chem. Phys. Vol. 18, 2018, pp. 6959–6969.

2. Farquharson L. M., Romanovsky V. E., Cable W. L., Walker D. A., Kokelj S. V., Nicolsky D. Climate Change Drives Widespread and Rapid Thermokarst Development in Very Cold Permafrost in the Canadian High Arctic. *Geophysical Research Letters*. 2019, № 46, p. 12.

3. Ji M., Kong W., Liang C., Zhou T., Jia H. & Dong X. Permafrost thawing exhibits a greater influence on bacterial richness and community structure than permafrost age in Arctic permafrost soils. *The Cryosphere*. 2020, № 14 (11), pp. 3907–3916.

4. Shengrong Zhang, Doudou Jin, Huijun Jin, Chunhai Li, Hu Zhang, Xiaoyin Jin, Jian Cui. Potential radon risk in permafrost regions of the Northern Hemisphere under climate change : a review. *Earth-Science Reviews.* Vol. 250. March 2024. P. 104684.

5. Chuanlei Liu, Jing Chen, Weihua Zhang, Kurt Ungar. Outdoor Radon Dose Rate in Canada's Arctic amid Climate Change. *Environ Sci Technol*. 2024, Jul 2. № 58 (26).

6. Seminsky K. Zh., Demberel S. The first estimations of soil radon activity near faults in Central Mongolia. *Radiation Measurements*. 2013. Vol. 49. Pp. 19–34.

7. Glover P. W. J., Blouin M. Increased radon exposure from thawing ofpermafrost due to climate change. *Earth'sFuture.* 2022. P. 10.

8. Сєдін В. Л., Бауск Є. А., Ульянов В. Ю., Бікус К. М. Шкала оцінювання акттивності тектонічниз розломів земної кори за інтенсивністю радоновиділення – застосування для об'єктів АЕС. *Основи і фундаменти : міжвідом. наук.-техн. зб. Київ. нац. ун-т буд-ва і архіт*. Київ, 2015. Вип. 37. С. 52–63.

9. Ковба В. В., Ульянов В. Ю., Сафронова В. С. Особливості проведення радонометрії з метою дослідження сейсмотектоніки на майданчиках АЕС у зоні вічної мерзлоти. *Безпека життєдіяльності в XXI столітті : тези допов. X Міжнар. наук.-практ. конф. (21–22 листопада 2024).* Дніпро : УДУНТ, ННІ ПДАБА, 2024. 109 с.

10. Ульянов В. Ю. Шляхи підвищення ефективності термопресіометрії. *Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту*. 2021. № 2 (92). С. 84–91.

11. Ye Yongjun, Zong Yifan, Li Mengyi, Song Bangzhi. Free radon production from uranium tailings under frozen and non-frozen conditions. *Journal of Radioanalytical and Nuclear Chemistry*. 2023. Vol. 334, iss. 3. Pp. 2195–2202.

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