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Radiogenic Heat Production in the Earth's Crust of Bulgaria: The Dominant Role of the Rhodope Massif

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***Abstract*— This report evaluates the radiogenic heat production (A) within the continental crust of Bulgaria, emphasizing the dominant role of the Rhodope Massif. The generation of thermal energy through the radioactive decay of uranium (U), thorium (Th), and potassium (K) is a primary component of the Earth's heat flow.**

The analysis first establishes a baseline for Bulgaria by assessing the average heat production levels across the main lithological units, utilizing previously published data on their radioactive element content. Subsequently, the study focuses on the Rhodope Massif, identified as the country's most significant heat-generating region due to radiogenic values that substantially exceed the national average.

Comparative results indicate that this elevated radiogenic heat is a major driver of regional geothermal activity and the high density of thermal springs. These findings provide essential data for crustal thermal modeling and the assessment of deep geothermal energy potential in Southern Bulgaria.

Keywords - Radiogenic heat production; Rhodope Massif; geothermal energy; radioactive decay; continental crust; energy independence.

I. INTRODUCTION

The increasing global demand for sustainable and carbon-neutral energy sources has revitalized scientific interest in the Earth's internal thermal regime. Aside from the Earth's primordial heat content remaining from its formation stages, the most significant internal heat source is the continuous radioactive decay of unstable isotopes of uranium (^{238}U and ^{235}U), thorium (^{232}Th), and potassium (^{40}K). These isotopes are non-uniformly distributed within the Earth's layers, with a primary concentration in the continental crust and upper mantle. The heat generated by their decay contributes decisively to the planet's overall thermal flux, governing tectonic processes and the formation of geothermal reservoirs. The mean surface heat flow of the Earth amounts to approximately 65 $mW.m^{-2}$ [1], while the mantle heat flow in continental regions is estimated at roughly 28 $mW.m^{-2}$ [2]. The significant discrepancy between these two values is attributed to the active production of heat through radiogenic processes within the continental crust itself. This crustal contribution often accounts for 40% to 60% of the total observed surface heat flow, depending on the lithological composition and tectonic history of the region [14]. The two primary isotopes of uranium, ^{238}U and ^{235}U, decay into stable lead isotopes— ^{206}Pb and ^{207}Pb respectively—with half-lives of 4.5 and 0.71 billion years. Uranium is defined as a widespread and highly mobile trace element within the composition of many rock types, particularly felsic igneous rocks. On the other hand, thorium (^{232}Th), with a half-life of 14.1 billion years, also decays into lead ^{208}Pb. Unlike uranium, thorium is chemically relatively inert and often exhibits a strong affinity for clay minerals and heavy accessory minerals. The sole unstable isotope of potassium is ^{40}K, which occurs in many rock-forming and clay minerals in significant concentrations of several percent, providing a constant and predictable component to the total radiogenic heat production. In the context of Bulgaria, the spatial distribution of these elements is controlled by the complex tectonic boundary between the stable Moesian Platform and the Alpine orogenic belt. Understanding this distribution is not only a matter of geophysical modeling but a prerequisite for assessing the country's sovereign energy potential. This report aims to evaluate the radiogenic heat production across Bulgaria's diverse geological domains, with a specific focus on the Rhodope Massif as a primary driver of the national thermal balance.

II. PHYSICAL AND GEOCHEMICAL FOUNDATIONS OF RADIOGENIC HEAT PRODUCTION

Radioactive decay fundamentally transforms mass into energy. In the initial stage, this energy is released as kinetic

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energy of the participating particles and nuclei (alpha and beta particles, and recoiling nuclei), subsequently transforming into gamma-ray and X-ray energy, as well as geo-neutrinos. With the exception of the negligible amount carried away by geo-neutrinos, all of this energy is converted into heat in the immediate vicinity of the decaying nucleus. The volumetric radiogenic heat production of a given rock, A (measured in $\mu W \cdot m^{-3}$), is calculated using the Rybach equation [3]:

$$A = 10^{-5}\rho(9.52c_U + 2.56c_{Th} + 3.48c_K \qquad (1)$$

Where ρ represents the rock density ($kg \cdot m^{-3}$) and c_U, c_{Th}, and c_K are the respective concentrations of uranium, thorium (in ppm), and potassium (in %). The quantities of these elements vary significantly depending on the rock type but follow distinct patterns due to their similar geochemical behavior during magmatic differentiation, sedimentation, and metamorphism.

- Igneous Rocks

During magmatic differentiation, U and Th, and to some extent K, tend to enrich within the more acidic (felsic) phases. The correlated behavior of uranium and thorium is driven by their similar ionic radii and high valency. Although absolute concentrations vary relative to the degree of differentiation, the average Th/U and K/U ratios remain relatively constant. According to established models [3] [4], the contribution to total heat production in igneous rocks is distributed as approximately 40% for U, 45% for Th, and 15% for K. It is precisely this enrichment in felsic phases that makes the granitoids of the Rhodope Massif a primary subject of interest for this study.

- Sedimentary Rocks

In sedimentary environments, uranium and thorium alter their behavior because uranium is easily oxidized ($U^{4+} \rightarrow U^{6+}$), becoming highly mobile in solution. Consequently, the Th/U ratio shows significant variations reflecting pH and redox conditions. The lowest radiogenic heat production values are observed in carbonate rocks (limestones and dolomites) and evaporites. Conversely, argillaceous sediments and shales are characterized by the highest values due to the high adsorption of radioactive elements onto fine-grained materials. Sandstones and conglomerates exhibit intermediate values, which are strongly dependent on the provenance of the detrital material and the geochemical conditions prevalent during sedimentation.

- Metamorphic Rocks

Metamorphic rocks inherit the radioactive composition of their protoliths (igneous or sedimentary), but the U, Th, and K content is redistributed according to the metamorphic grade. Generally, there is a trend of decreasing concentrations of these elements as the metamorphic grade increases, driven by dehydration and the partial migration of fluids. The depletion of U and Th caused by progressive metamorphism is particularly pronounced in granulite facies. The ions U^{4+} and Th^{4+}, characterized by large ionic radii, can exist only in eightfold coordination with oxygen and cannot be accommodated within the tightly packed structures formed under higher pressures and temperatures. Consequently, U and Th tend to migrate upward within the Earth's crust as a result of dehydration reactions or partial melting near the base of the crust [3]. Metamorphic mineral transformations lead to the loss of volatiles, with the migration of U and Th being accompanied by H_2O and/or CO_2. Potassium appears to be relatively stable and is not significantly affected by these processes.

III. Regional Analysis and Quantitative Model of Radiogenic Heat Production in Bulgaria

The territory of Bulgaria is characterized by a complex geological structure resulting in significant variations in the thermal field.

The primary division is defined by the boundary between the stable Moesian Platform to the north and the tectonically active structures of the Alpine Orogen to the south. While the north remains energy-passive due to its thick sedimentary cover of limestones and dolomites, the southern regions function as a massive crustal heat source. This is attributed to the exposed crystalline basement, enriched with Paleozoic and Tertiary granitoids, which generate intense autochthonous heat.

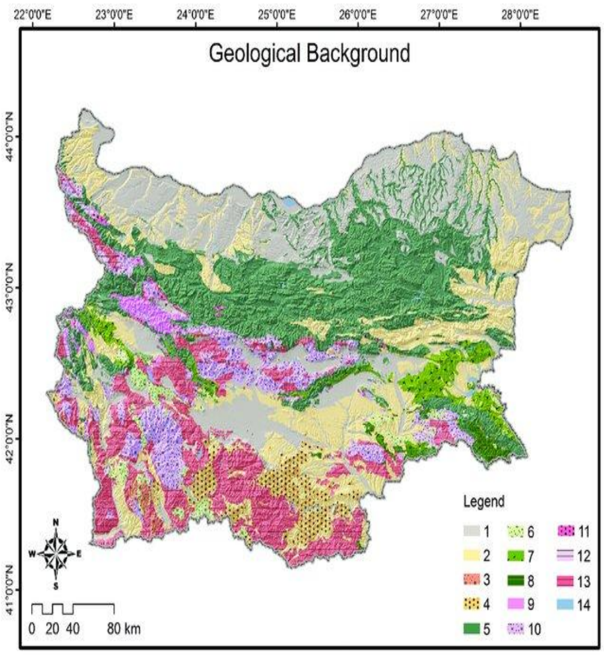

Fig 1: Geological map of Bulgaria showing the main types of rocks (after Cheshitev and Kanchev, 1989). Legend: 1 -Quaternary sediments; 2 - Neozoic sedimentary rocks; 3 -Neozoic intrusive rocks; 4 -Neozoic volcanic and volcano-sedimentary rocks; 5 -Mesozoic sedimentary rocks; 6 -Mesozoic intrusive rocks; 7 -Mesozoic volcanic and volcano-sedimentary rocks; 8 -Mesozoic metamorphic rocks; 9 -Paleozoic sedimentary rocks; 10 -Paleozoic intrusive rocks; 11 -Paleozoic volcanic

and volcanosedimentary rocks; 12 -Paleozoic metamorphic rocks; 13 - Precambrian metamorphic rocks; 14 -water.[5],[6]

To precisely determine the total energy capacity (Q_{total}) of the country, a computational model has been applied that categorizes these regions into three specialized lithological domains. The total heat generation for the 111,000 km^2 territory is calculated using the equation:

$$Q_{total} = \sum(A_i . S_i . D_i) \quad (2)$$

Where A_i is the radiogenic production, S_i is the occupied area, and D_i is the thickness of the active layer in the upper crust (fixed at 10 km). In this model, Bulgaria's area is weighted according to three primary types of geological environments:

- Sedimentary Basins (around 55% of the area):

Comprising the Moesian Platform and the Thracian Depression. Dominated by Mesozoic and Cenozoic sediments, primarily limestones, dolomites, marls, sandstones, and evaporites. These are typically characterized by low radiogenic isotope concentrations..

- Folded Mountain Ranges (around 25% of the area):

Including the Balkan Mountains (Stara Planina) and the Srednogorie zone. They represent a transition zone with a mixed composition of Paleozoic and Mesozoic sediments and volcanics. Includes flysch, argillites, andesites, and tuffs (common in the Srednogorie zone), along with low-grade metamorphics such as phyllites and chlorite schists.

- Crystalline Massifs (around 20% of the area):

Covering the Rhodopes, Rila, Pirin, and Sakar. This is the country's energy core, with a high-grade metamorphic and igneous complexes. Primarily composed of gneisses, migmatites, and amphibolites, along with massive intrusions of granites, granodiorites, and syenites. These lithologies host the highest concentrations of U, Th, and K.

The volumetric radiogenic heat production rate (A) for each lithological domain was derived as a weighted average based on previously published geochemical and petrophysical datasets of radionuclide concentrations in Bulgaria [11]. The spatial distribution and surface area (S_i) of the respective domains were calculated via 1:500,000 Geological Map of Bulgaria. The thickness of the radiogenic active layer (D_i) was fixed at a conservative baseline of 10 km, corresponding to the average depth of the upper brittle continental crust where granitoids and metamorphic rocks are predominantly concentrated. The total power (Q_{total}) was mathematically integrated by aggregating the discrete thermal contributions of each lithological zone, ensuring a scalable numerical model for regional geothermal forecasting.

The physical parameters and power distribution are presented in Table 1.

TABLE 1 RADIOGENIC HEAT PRODUCTION IN BULGARIA

Domain (Map Groups)	Area (S) in km^2	Density (ρ) in kg/m^3	Production (A) in μW/m^3	Calculated Power (P)
Sedimentary Basins	61000 (55%)	2450	1.00	~ 610 GW
Mountain Ranges	27700 (25%)	2600	1.50	~ 415 GW
Crystalline Massifs	22300 (20%)	2700	2.80	~ 624 GW
Total (Bulgaria)	111 000	—	—	1649 GW

The calculations indicate that the total radiogenic heat power in the upper crust of Bulgaria amounts to approximately 1649 GW. The average radiogenic generation per unit area is 14.8 mW/m², representing nearly 40% of the total continental heat flow.

To understand the actual significance of different geological structures for Bulgaria's energy balance, it is necessary to compare the surface area they occupy with the thermal power they actually generate.

In Sedimentary Basins, which cover more than half of the country's territory (55%), a significant deficit in heat production is observed—they contribute only 37% of the total radiogenic power. This contrast confirms that the massive accumulations of limestones and dolomites in Northern Bulgaria are energy-passive.

At the same time, the situation for Crystalline Massifs (Rhodopes, Rila, Pirin, and Sakar) is fundamentally different. Although they occupy only 20% of Bulgaria's land area, their contribution to the total power is nearly 38% (624 GW). This means that a unit area of the crystalline basement in Southern Bulgaria generates nearly twice as much energy compared to sedimentary regions.

This visual contrast clearly demonstrates that the Rhodope region and the crystalline massifs function as the country's "energy core."

The presented chart illustrates a key correlation: geographic distribution does not correspond to energy capacity.

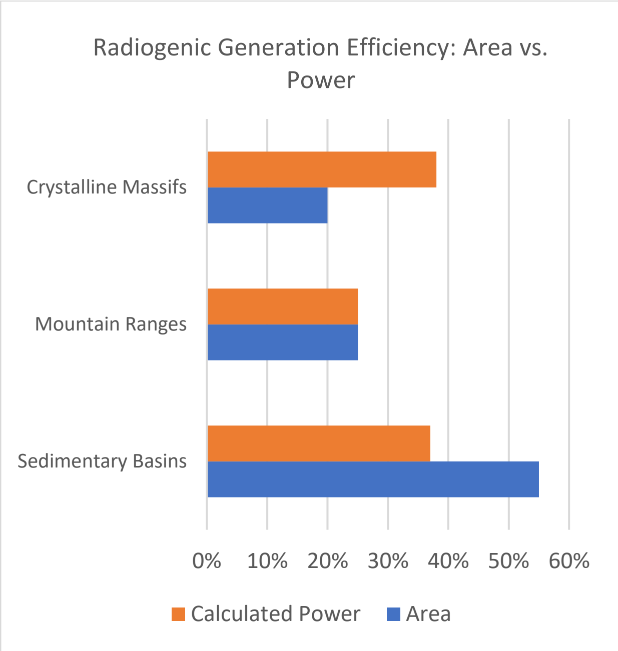

Fig 2 Radiogenic Generation Efficiency: Area vs. Power

IV. The Dominant Role of the Rhodope Massif

The analysis of radiogenic radiation in Bulgaria unequivocally defines the Rhodope Massif as a fundamental energy pillar in the country's architecture. Its dominant role is not a random statistical anomaly but a direct consequence of the complex geological evolution of the Balkanides, which has transformed the region into a unique thermal generator. While the majority of the country's territory is covered by Paleozoic and Cenozoic energy-passive sediments, the Rhodope Massif exposes the ancient crystalline basement of the continental crust. Composed of high-grade metamorphic rocks such as gneisses and migmatites, intruded by massive Paleozoic granitoids, this basement functions as a natural accumulator of heavy radioactive isotopes [8]. In these structures, the concentration of radiogenic elements is many times higher than in the Moesian Platform, turning the massif into a constant source of energy generated at depth [9].

This internal power is complemented by the region's specific fault tectonics, characterized by deep structural disturbances. These are of critical importance to the thermal regime, as they allow groundwater to circulate at significant depths where it absorbs heat from energy generated by radioactive decay, returning to the surface as active hydrothermal systems [6]. It is precisely the presence of this crystalline heat source that causes the uniquely high temperature gradient of the mineral springs in Southern Bulgaria, making them a direct manifestation of the endogenous energy of the subsurface.

Beyond statistical data, the geothermal potential of the Rhodope Massif assumes a strategic dimension that exceeds the scope of conventional thermal water utilization. The high density of heat production defines the region as the only zone in Bulgaria suitable for implementing innovative systems for extracting energy from hot dry rocks. The centralized nature of conventional energy sources renders them vulnerable to hybrid threats or physical damage to transmission infrastructure. On the other hand, the geothermal capacity of Southern Bulgaria allows for the establishment of a decentralized network of energy hubs located directly above zones of peak radiogenic activity . Such a distributed energy architecture enhances the resilience of the national economy during emergencies, ensuring an uninterrupted power supply for critical infrastructure [7]. Thus, the massif can be positioned as a primary factor in the national strategy for energy independence, offering a resource for the production of clean baseload electricity that is entirely independent of climatic conditions and fluctuating renewable sources.

V. Conclusions

The conducted research on radiogenic heat production in Bulgaria confirms that the country possesses a significant and largely untapped energy asset within its crystalline basement. The integrated analysis of geological, geophysical, and energy data reveals a profound regional asymmetry between the energy-passive sediments of Northern Bulgaria and the highly productive thermal core of the Rhodope Massif .

In practical terms, the quantitative model developed in this study serves as a foundational baseline for macro-level geothermal zoning and regional energy planning in Southern Bulgaria [13]. Specifically, these findings can be directly applied by resource developers and policymakers to identify optimal geographic locations for Enhanced Geothermal Systems and Deep Hot Dry Rock exploration [12]. Furthermore, incorporating this radiogenic heat data into national energy security frameworks will facilitate the strategic deployment of decentralized, climate-independent baseload power hubs, directly accelerating Bulgaria's transition toward sustainable energy sovereignty.

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