УДК 550.36

ИТОГИ ИЗУЧЕНИЯ ТЕПЛОВОГО ПОТОКА В НИГЕРИИ

Л. АКИНЬЕМИ[1)]***, В. И. ЗУЙ***[2)]

[1)]*Университет Олабисди Онабанджо, Аго-Ивойе, Огун, Нигерия*
[2)]*Белорусский государственный университет, пр. Независимости, 4, 220030, г. Минск, Беларусь*

Традиционный подход к измерению теплового потока включает два параметра: геотермический градиент и теплопроводность горных пород, слагающих рассматриваемый интервал глубины. Геотермический градиент определяют из термограммы, зарегистрированной в скважине, а теплопроводность – путем лабораторных измерений отобранных образцов горных пород. Известны вариации этого подхода относительно геотермического градиента и значений теплопроводности. Однако на многих площадях отсутствуют скважины для регистрации термограмм или по крайней мере для получения нескольких замеров температуры на промежуточных забоях, в результате чего традиционный метод нельзя применить. В Нигерии, в районах, где нет глубоких скважин, был широко использован новый метод определения теплового потока, базирующийся на оценке глубины кровли и подошвы магнитоактивного тела при анализе карт магнитного поля. Подошва магнитоактивного тела соответствует температуре поверхности Кюри, ниже которой горные породы теряют магнитные свойства. Известно, что это происходит при температуре около 580 °С, которая несколько варьируется в зависимости от содержания магнетита в магнитоактивном теле. Тепловой поток вычисляют путем умножения геотермического градиента в этом интервале глубины на теплопроводность горных пород. Имеется ряд разрозненных значений теплового потока в Нигерии, рассчитанного обоими методами. Составлена предварительная карта теплового потока, основанная на доступных данных. Сравнение величин теплового потока, определенных двумя методами, для нескольких регионов страны позволило выявить их соответствие.

Ключевые слова: геотермия; тепловой поток; магнитное поле; изотерма Кюри; Нигерия.

SUMMARY OF HEAT FLOW STUDIES IN NIGERIA

L. AKINYEMI[a]***, V. I. ZUI***[b]

[a]*Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria*
[b]*Belarusian State University, 4 Niezaliežnasci Avenue, Minsk 220030, Belarus*
Corresponding author: V. I. Zui (zui@bsu.by)

A traditional approach for heat flow determination requires two parameters. They are a geothermal gradient and heat conductivity of rocks comprising the considered depth interval. The geothermal gradient is determined from a thermogram recorded in a wellbore and the heat conductivity is obtained from the laboratory measurements of selected rock samples. There are some variations of this approach to both get the gradient and heat conductivity values. However, there are many areas without boreholes to register their thermograms, or at least to have several temperature readings at intermediate positions of bottom holes and traditional methods of heat flow determinations cannot be used. Recently another method was proposed to estimate heat flow. It was derived from spectral analysis of magnetic field. During last years it

Образец цитирования:
Акиньеми Л, Зуй ВИ. Итоги изучения теплового потока в Нигерии. *Журнал Белорусского государственного университета. География. Геология.* 2019;2:121–132 (на англ.).
https://doi.org/10.33581/2521-6740-2019-2-121-132

For citation:
Akinyemi L, Zui VI. Summary of heat flow studies in Nigeria. *Journal of the Belarusian State University. Geography and Geology.* 2019;2:121–132.
https://doi.org/10.33581/2521-6740-2019-2-121-132

Авторы:
Лукман Акиньеми – научный сотрудник.
Владимир Игнатьевич Зуй – доктор геолого-минералогических наук, доцент; профессор кафедры региональной геологии факультета географии и геоинформатики.

Authors:
Lukman Akinyemi, researcher.
olaakinyemi83@gmail.com
Vladimir I. Zui, doctor of science (geology and mineralogy), docent; professor at the department of regional geology, faculty of geography and geoinformatics.
zui@bsu.by

was widely used in Nigeria for areas where deep boreholes are absent. It uses estimates of depths to the base and bottom of the causative body derived from analysis of the magnetic field maps. The base of the causative body corresponds to the depth of the Curie surface at which rocks lose their magnetic properties. It is known that it happens at the temperature around 580 °C that slightly varies depending on the content of magnetite within the causative body. The temperature at the top of this body is estimated. The heat flow density can be calculated knowing the geothermal gradient within this depth interval and heat conductivity of rocks. A preliminary heat flow density map was compiled based on all accessible heat flow data. A comparison of heat flow data from several regions of the country, determined using both methods provides rather good agreement.

Keywords: geothermics; heat flow; magnetic field; Curie isotherm; Nigeria.

Introduction

Nigeria has a poor production of electricity and its distribution. Electricity generation is on a thermal plant (up 66.7 %) and hydro power plant – 33 % of the total power production. Of 170 million of population, about 45 % have access to electricity, which is easier within urban areas. During last decades, using of renewables, including geothermal energy, was spreading worldwide, and the awareness of energy sector, as well as federal and local authorities, on such energy raised in Nigeria. Investigations of terrestrial temperature were carried out in hundreds of exploration wells drilled for oil and gas.

The geothermal gradient and heat flow are frequently used parameters in geology as important indicators of the thermal state of the crust and its sedimentary cover. They are useful for estimating geothermal resources, prospecting for oil and gas fields, considering the regional tectonics, geodynamics, etc. The temperature is one of factors controlling the hydrocarbon generation. Temperature-depth curves are recorded by logging in open wellbores in a few hours or days after the interruption of drilling.

They reflect transient phenomena caused by the drilling mud circulation. The steady state diagrams are seldom for oil wells of Nigeria. In most of publications, researchers analyzed these curves when the thermal regime was not restored, or sometimes they use several temperature readings at intermediate bottom hole positions during drilling of the well (BHT), which permit to determine the geothermal gradient.

Exploratory and development wells have been drilled in the Niger Delta since 1956, when first oil was first discovered in the country [1]. Since that time, a number of temperature-depth logs were recorded in these, or measurements of individual temperature values, fulfilled at a number of intermediate positions of bottom holes in a course of oil wells drilling. Later these temperature data were used to determine heat flow density.

However, until now the territory of the country was geothermally studied mainly within deep sedimentary basins. Such measurements were fulfilled as a rule within crustal blocks promising for oil exploration. No direct temperature measurements are available in other parts of the region. Nigerian researchers have done a number of heat flow estimates derived from the magnetic field analysis. Such data comprise for today around 50 % of available heat flow determinations. The article summarizes the existing heat flow information for the whole territory of the country.

Traditional methods for heat flow determination

Traditional approach to calculate heat flow density assumes a separate determination of geothermal gradient and a heat conductivity of rocks from the considered depth interval. In result multiplying the gradient by heat conductivity of rocks from the same depth interval, results in its heat flow value [2]. The geothermal gradient is a well-known result of the division the temperature at the base of the considered depth interval T_2 minus the temperature at its top T_1 by the interval length $z_2 - z_1 = L$ (fig. 1).

$$\text{grad}\, T = \Delta T / \Delta h = (T_2 - T_1)/(z_2 - z_1).$$

Two temperature values T_2 and T_1 could be used as readings from a thermogram at two depths z_2 and z_1 or two temperatures at two intermediate positions of a bottom hole in the same well could be used. The heat conductivity of selected rock samples from a drill core, taken from the considered depth interval, is determined by laboratory measurements. When the thermogram was not recorded, these two temperature values could be taken as temperatures recorded at two different bottom hole positions within drilled deep wells.

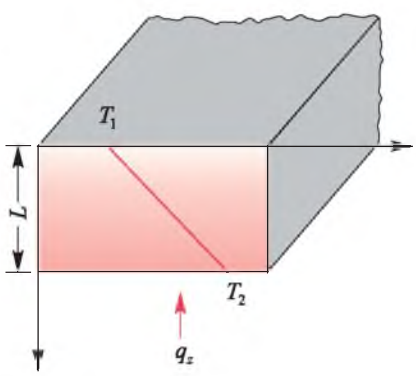

Fig. 1. Temperature profile and heat flow q_z within rocks with uniform heat conductivity

It is assumed that the considered depth interval is represented by uniform type of rocks, otherwise it could be accepted as, for instance, the arithmetic mean from results obtained after measurements of several samples from the same interval. There are several modifications of this method. This simple method is used also when porous or cracked rocks comprise the considered depth interval. However, besides pure heat conduction, a convective component of heat transfer takes place here and heat flow calculations require corrections to be applied [2]. In other situations observed heat flow values are subjected to corrections, e. g. for topography, ground water circulations or climatic perturbations. The most reliable data are included into heat flow catalogues.

The distribution of available onshore heat flow data within different crustal blocks are rather uneven. There are many boreholes drilled within deposits of mineral resources, for instance within oil and gas fields and they are rather sparse within territories without such mineral deposits. Some exclusion represent wells for water supply for settlements or industrial enterprises. However, they are rather shallow and geothermal regime within their vicinity is subjected noticeably to groundwater circulation, which influences observed heat flow values within studied intervals. Moreover, the thermal logging within new finished deep wells are frequently fulfilled only after a few days and the time elapsed after their drilling was finished and recording of thermograms was undertaking is not enough for their field disturbed by the drilling to return to the steady state condition. Usually such thermograms reflect transient features and are not acceptable for accurate heat flow determinations without considerable corrections.

Method to heat flow estimate from the magnetic field analysis

There are many crustal blocks where heat flow determination could not be fulfilled using the described and traditional approach. One of indirect approaches to estimate heat flow density frequently used during last decades is the method to derive heat flow from processing and analysis of maps of the magnetic field. The method is aimed to determine the depths to the top and base of the magnetic causative body within the earth's crust. It is well known that magnetic properties of rocks disappear when they reach the Curie temperature, which many authors consider to be around 550–580 °C.

When temperature of rocks exceeds the Curie point, magnetic materials lose their magnetisation. At the same time, it is considered that for temperature exceeding 580 °C, those materials begin encountering the ductile deformation [3]. The Curie point determination was considered in a number of publications [4–10]. It was shown that spectral analytical method could be regarded to estimate of the Curie point depth (CPD).

The spectral method of analysis was developed by [11; 12]. Later it has been used in the analysis of magnetic anomalies in particular for the determination of average depth to the top of magnetic basement and for the computation of crustal thickness, the Curie point isotherm, etc. [6; 13; 14].

The Fourier transformation of the aeromagnetic data to estimate the energy (or amplitude) spectrum by transforming the spatial data into frequency domain is used in most cases and the spectrum analysis techniques is applied for CPD determination. The method of Spector and Grant [12] allows estimating the average depth to the top of the magnetized layer from a slope of the log power spectrum. The method of Bhattacharyya and Leu [15] gives a possibility to estimate the depth to the centroid of the causative body by means of a single anomaly interpretation. Later Okubo and his colleagues [16] combined both methods, developed an algorithm for regional geomagnetic interpretation, and applied it to the geothermal exploration.

There are several applications of described approach to calculate the depths to the top of the causative body and base of the Curie point. If the magnetization of a set of two-dimensional bodies is completely random and uncorrelated, the radial average of the power density spectra of the total field anomaly, $P(k)$, could be simplified as follows [17; 18]:

$$P(k) = A_1 \exp\left(-2|k|Z_t\left(1 - \exp\left[-|k|(Z_b - Z_t)\right]^2\right)\right),$$

where A_1 is a constant; Z_t and Z_b represent the depths to the top and bottom of the magnetic body; respectively k denotes the wave number of the magnetic field.

Two steps are necessary to evaluate CPD, the first step to estimate the depth to centroid h_0, of a magnetic source from the slope of the longest wavelength part of the spectrum, using equation [6; 16; 19]. The centroid depth of magnetic sources can be calculated from the low-wavenumber portion of the wavenumber-scaled power spectrum as [20]

$$\ln\left[\frac{\sqrt{P(k)}}{|k|}\right] = \ln A - 2\pi|k|h_0,$$

where A is a constant.

The second step permits estimating the depth to the top boundary h_1 from the slope of the second longest wavelength part of the spectrum [6; 16; 19].

$$\ln\sqrt{P(k)} = \ln B - 2\pi|k|h_1,$$

where B is the sum of constant independent of $|k|$.

The basal depth h_b is calculated from the equation [6; 16; 21].

$$h_b = 2h_0 - h_1,$$

where h_0 denotes centroid depth; h_1 represents to the top boundary. An example is shown in fig. 2.

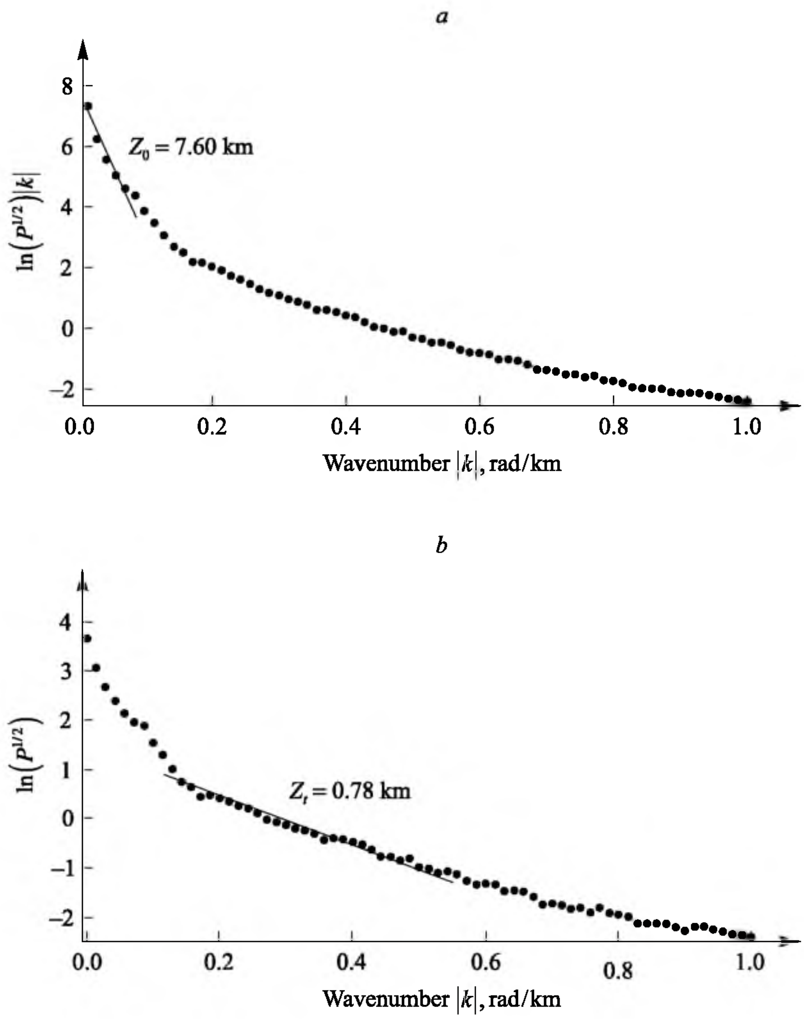

Fig. 2. An example of radially average power for estimation of CPD using the two-dimensional magnetic anomaly data for the block 5 of the model considered for the Ikogosi warm spring: *a* – an example to estimate the Z_0 depth and *b* – an example to estimate the Z_t depth.
Source: [22], modified

Depths of 7.60 and 0.78 are obtained as the centroid and top bound using the gradient of spectra defined as $\ln\sqrt{P(k)}|s|$ and $\ln\sqrt{P}$, where $|k|$ is the wavenumber and $P(k)$ is the radially average power spectrum.

Different researchers point out that the Curie temperature depends on magnetic mineralogy. The Curie temperature of magnetite (Fe_3O_4), the most common magnetic material in igneous rocks, is around 580 °C, however, an increase in titanium (Ti) content of titanomagnetite ($Fe_{2-x}Ti_xO_3$) causes a reduction in Curie temperature. It is believed that in most cases it is (550 ± 30) °C [6]. The Curie point temperature is strongly influenced by the amount of titanium. The estimated value of 580 °C [23] is considered as the case in this study. Using this Curie point temperature of 580 °C and the derived CPD, it is possible to calculate the geothermal gradient within the considered area. The thermal conductivity is usually accepted to be 2.5 $Wm^{-1}{}°C^{-1}$ [24; 25].

Geology of the region

Nigeria lies between latitudes 4° and 14° N, and longitudes 2° and 15° E. Rocks, comprising the crust within the country, have different age and origin. The Precambrian basement spread over almost 48 % of this region (fig. 3). Deep basins exist within the remaining 52 % of the country, where sediments have Cretaceous to the younger age [22]. Over 80 volcanoes exist within both the Biu and Jos plateaus with basaltic lava flows [26]. The Niger River with its Benue tributary is the principal river of West Africa and runs its waters to the Atlantic Ocean.

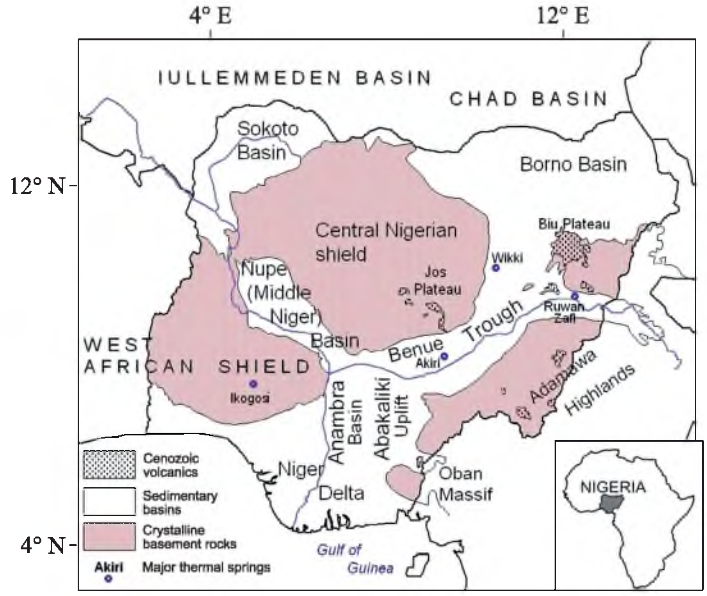

Fig. 3. Geological subdivision and the main crustal blocks in Nigeria.
Four circles indicate positions of warm springs: Akiri (53.5 °C), Wikki (32 °C) and Ruwan Zafi (54 °C), as well as Ikogosi (37 °C).
Source: [27]

Sedimentary basins originated when the Gondwana started to split, opening Atlantic Ocean, in the early Cretaceous time and formed the Pan African Rift system in the West African terrain. These basins are filled with sediments of different thickness, subjected later to tectonic deformations through Cretaceous to Neogene time. Their deepest parts are more than 9–12 km [28] and the widest spread corresponds to the Niger Delta [29].

The Benue Trough is subdivided into the Upper, Middle and Lower Benue troughs. The latter one includes the Anambra Basin, Abakaliki Uplift with the maximal thickness of sediments up to 6 km. Sedimentary cover thickness is around 4 and 1 km in the Borno and Sokoto basins, respectively.

An important rifting event within the West Africa happened during the Cretaceous time in result the equatorial Atlantic opening led to the generation of intraplate rifts, including the Benue Rift and a series of Cretaceous elongate basins in West Africa.

The Central Nigerian Shield with the Jos Plateau in the centre of the country and the West African Shield occupy the central and northwestern parts of the area. The latter one extends through the border into the Benin territory. The Nupe (Middle Niger) and Sokoto basins in their northern part and the Borno Basin within eastern Nigeria, as a part of the Chad Basin, separate both shields. The Chad Lake is in the extreme north-east of the country, which Nigeria shares with Niger, Chad and Cameroon. The Sokoto Basin is a part of the vast Iullemmeden Basin, which extends through the border into the Niger territory. The Iullemmeden, Chad, Taoudeni and Sinegal-Mauritanian basins belong to the main sedimentary basins of the West Africa. The latter two are outside frames of the fig. 3 to the north.

The Adamava Highlands (monocline) is extended along the southeastern border of the country and continues into Cameroon area. The Niger Delta region, which is, home of the large oil industry, where Nigeria has a total around 160 oil fields, is sitting directly on the Gulf of Guinea on the Atlantic Ocean. The Biu Plateau in the eastern part of the country is located in between the Borno Basin and the Benue Trough.

Available heat flow data

The available heat flow data could be subdivided into three categories. The first category of heat flow values is based on thermograms of wells, or temperature readings done at intermediate positions of bottom holes during drilling deep wells. The second category represents estimated heat flow values derived from processing of the aeromagnetic data (indirect approach) for a number of localities. Finally, new heat flow dencity (HFD) estimates based on published positions of CPD are included into the third group.

First wells, drilled until depths usually less than 3500 m within the Niger Delta in the middle of fifties, discovered oil. Since those time terrestrial temperatures and geothermal gradients were based on thermograms or bottom hole temperature data in the Niger Delta [30], Anambra, Sokoto [9; 31] and Borno [32] basins. Sokoto Basin extends into territories of Niger, Chad, Central African Republic and Cameroon. The information on geothermal field of the Nupe, Borno and Sokoto basins was published also by [24; 32; 33].

Indirect heat flow estimates are based on CPD positions at which the dominant magnetic mineral in the crust becomes paramagnetic due to the effect of increasing temperature above 580 °C [34; 35]. As it was mentioned, to estimate heat flow density we need the geothermal gradient and thermal conductivity. The gradient is calculated from the Curie isothermal depth and then heat flow is estimating using this geothermal gradient and the averaged heat conductivity of rocks (2.5 $Wm^{-1}K^{-1}$). In most of publications the surface temperature is accepted to be 0 °C [36], though the annual average temperature at the Niger Delta is around 20 °C [25; 37]. Preliminary estimates show that when accepting the temperature at the top of causative body to be 0 °C, instead of its real value, it will result in an error in heat flow calculation, which usually does not exceed 5 mW/m^2.

Methods for estimating the CPD are classified into two categories: based on examination of isolated magnetic anomalies and those that examine patterns of these anomalies. Both methods provide the relationship between the spectrum of magnetic anomalies and the depth of a magnetic source by transforming spatial data into frequency domain [38].

In addition to published data in mentioned above articles, new heat flow estimates were fulfilled based on printed CPD positions. They are included into the table.

New heat flow density estimates

Longitude	Latitude	Z_t	Z_b	Reference	Heat flow density, mW/m^2
9.25	9.25	2.04	17.04	34	85.1
9.75	9.25	2.50	24.1	34	60.2
9.25	8.75	2.14	20.66	34	70.2
9.75	8.75	1.98	19.66	34	73.8
9.25	8.25	1.20	17.92	34	80.9
9.75	8.25	1.40	17.32	34	83.7
9.5	9.25	2.0	19.20	34	75.5
9.50	8.75	3.20	27.40	34	52.9
9.50	8.25	1.70	19.18	34	75.6
9.50	9.00	1.50	20.58	34	70.5
9.50	8.00	1.84	24.12	34	60.1
9.25	8.25	2.08	27.32	34	53.1
9.75	8.25	1.86	20.78	34	69.8
9.50	8.25	1.65	23.19	34	62.5
10.35	9.75	2.94	10.00	22	119.59
10.55	9.75	2.97	9.05	22	168.39
10.25	9.70	2.62	11.56	22	134.22
10.75	9.65	1.61	8.21	22	144.76
10.55	9.65	4.47	10.30	22	125.00
10.25	9.50	3.67	9.55	22	147.23
10.50	9.50	3.35	11.06	22	91.92
10.75	9.50	1.15	9.39	22	135.94
10.25	9.30	3.75	15.04	22	144.76
10.70	9.40	2.94	10.17	22	111.94

Ending table

Longitude	Latitude	Z_t	Z_b	Reference	Heat flow density, mW/m^2
10.55	9.60	4.32	9.55	22	139.36
10.45	9.25	3.24	12.35	22	89.71
10.75	9.25	1.21	9.92	22	149.95
10.40	9.60	2.11	15.41	22	94.1
10.34	9.25	3.98	9.22	22	157.3
4.46	7.48	0.852	21.91	40	66.2 (63.10)
5.10	7.48	0.945	13.40	40	108.2
5.70	7.48	0.878	13.46	40	107.7
5.12	7.38	0.727	12.35	40	117.4
5.16	7.43	0.780	14.42	40	100.6
5.17	7.30	0.645	12.37	40	117.2
5.50	7.24	0.646	14.94	40	97.1
5.17	7.16	0.666	11.48	40	126.3
5.90	7.16	0.626	16.68	40	86.9
4.46	7.16	0.713	20.11	40	72.1
4.46	7.24	0.766	13.24	40	109.5
4.77	7.40	–	–	40	104.42
4.46	7.36	0.807	20.16	40	71.9
4.58	7.46	0.791	17.83	40	81.3
5.60	7.40	1.025	15.33	40	94.6
4.59	7.20	0.735	18.61	40	77.9
5.50	7.37	0.901	13.52	40	107.24
5.83	7.62	–	–	40	102.26
4.60	7.35	0.812	11.77	40	123.2
5.17	7.48	0.827	13.70	40	105.8
5.12	7.48	0.827	13.86	40	104.6
4.58	7.22	0.646	15.01	40	96.6
4.46	7.33	0.922	14.35	40	101.0
5.11	7.48	1.000	13.89	40	104.4

Heat flow density map

All accessible heat flow data, determined using thermograms of deep boreholes and bottom hole temperature readings at intermediate positions of wells in drilling, as well as heat flow values determined from the spectral analysis of available magnetic field maps were used to compile a preliminary heat flow map for the whole territory of Nigeria (fig. 4). The number of individual heat flow values approaches to 360. Small squares (studied deep wells) and circles (estimates derived from the magnetic field analysis) show positions of individual localities with available HFD data.

Discussion

Available heat flow data are nonuniformly distributed within the territory of the country, where sedimentary basins studied much better. Only its single estimates were reported for the Central Nigerian and West-African (Benin-Nigeria) shields. No data exists from the Oban Massif, Jos and Biu plateaus, with relatively young volcanism.

Profiles A – A and B – B through best studied crustal blocks are shown in fig. 5 and 6.

Along the A – A profile, crossing the whole of Nigeria from Atlantic shore to the Chad Lake, there are many observations. Heat flow varies considerably along the profile from around 25 in the Niger Delta till 150 mW/m^2 in the Benue Trough near the Wikki and Ruwan Zafi hot springs in the northeast of the country. The general tendency of gradual increase of heat flow from southwest to northeast is obvious. Several peaks in this curve could be interpreted as an influence of the geologic structure of individual crustal blocks. But it is necessary to keep in mind, that heat flow curve along this profile was based both on traditional approach (thermograms recorded in oil wells) and on its indirect estimates, obtained by different researchers at different time.

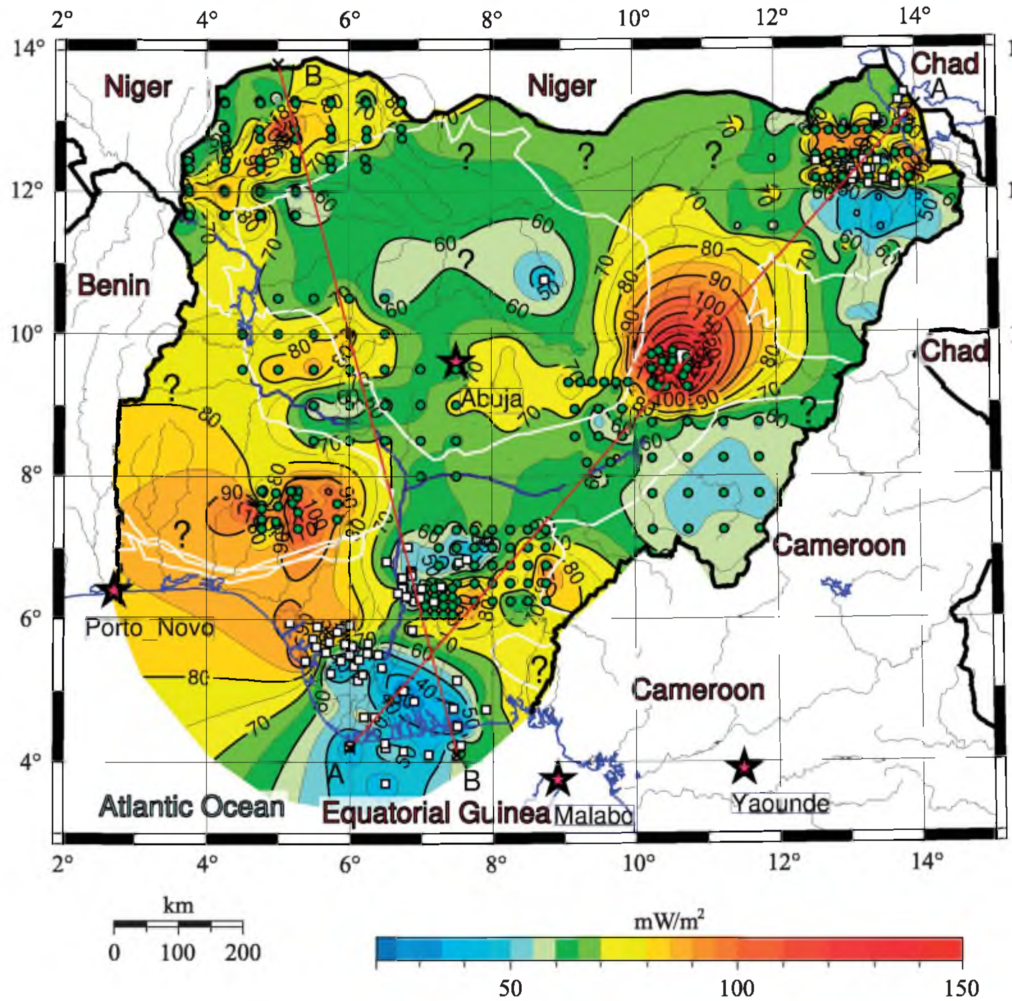

Fig. 4. Preliminary map of the heat flow density in Nigeria.
White squares show positions of geothermally studied wells;
green circles show available indirect heat flow density estimates derived
from the magnetic field analysis. Areas with absent heat flow data shown by the symbol «?».
The A – A and B – B profiles cross the main geologic structures (shown by red lines)
of the country with a wide range of heat flow variations from 35–40 until 140–150 mW/m^2

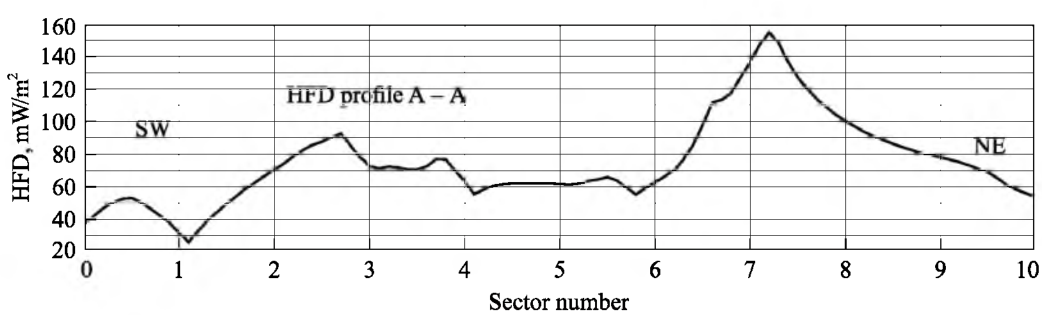

Fig. 5. Heat flow density profile A – A

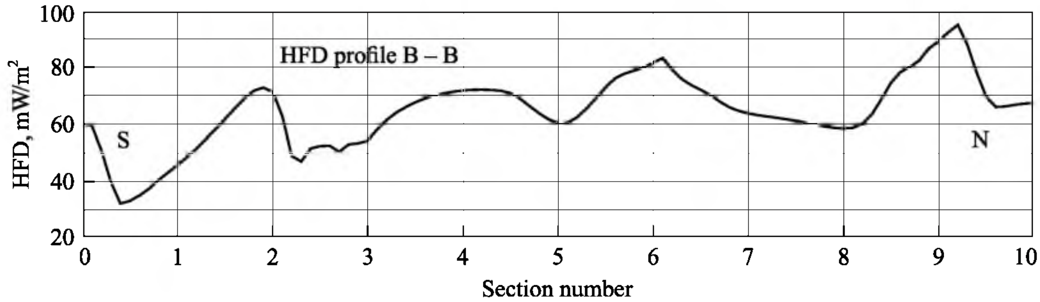

Fig. 6. Heat flow density profile B – B

The meridional profile B – B shows that the heat flow ranges from 30 until 90 mW/m^2. It reflects rapid heat flow changes in the meridional direction and a general tendency of its increase from south to north. This profile crosses geologic units of different age.

Heat flow values range within the country approximately from 35 to 140–145 mW/m^2. A low heat flow anomaly of 40–50 mW/m^2 is traced in the central part of the Niger Delta. It increases in all directions outwards of this cold zone to 70–80 mW/m^2.

A high heat flow anomaly above 100 mW/m^2 exists within the studied parts of Borno Basin. It joins with another anomaly around the Wikki warm spring and they both form a vast positive anomaly in the eastern part of Nigeria. A high heat flow above 80–100 mW/m^2 revealed around the Ikogosi warm spring. The Sokoto Basin in the north of the country is shown by increased heat flow to 70–80 mW/m^2. Its similar range is typical for the central part of the Nupe Basin.

Rather differentiated heat flow pattern is in the Anambra Basin. Heat flow values change from 50–60 mW/m^2 in its northern part to 80 mW/m^2 southward. Heat flow density of the Nigerian part of the Adamava highlands and the central part of the Benue Trough varies in limits of 55–60 mW/m^2 increasing to 70 mW/m^2 to the Wikki spring.

Geothermal observations in the southern part of Nigeria (Niger Delta and Anambra Basin) were studied by [31; 39–42]. Studies of geothermal field in this structure were actively conducted recently [43–49]. Results of heat flow studies in the Niger Delta were also published [50–52]. Heat flow density here varies within the Niger Delta from 38.9 to 89.6 mW/m^2 [46]. In the eastern part of the structure, it ranges from 29 to 55 mW/m^2 with an average value of 42.5 mW/m^2. Lower heat flow (less 35 mW/m^2) was observed for the central parts of the Niger Delta within the central swamp near Atlantic shore [1]. Within Anambra Basin it varies from 48 to 76 mW/m^2 [31].

It was reported that geothermal gradients in deep wells within the Niger Delta, show a continuous and non-linear relationship with depth, it increases with diminishing sand percentages. As sand percentages decrease eastwards and seawards, thermal gradient increases. A number of thermograms here have a concaved shape to depth axis [48]. It was reported that the movement of fluids in the Niger Delta influence the thermal field pattern and heat flow distribution within the Basin. This concerns both the effects of upward and downward groundwater movements within aquifers, petroleum, connate and juvenile water [1].

Only one locality for Precambrian crustal blocks geothermally studied in Nigeria, is the Ririwai Ring Complex (heat flow is 38.5 mW/m^2). Measurements were fulfilled there in available boreholes [53]. This value is close to data for other Precambrian shields of the world.

For the Nigerian part of the Chad Basin the heat flow derived from the magnetic field analysis ranges from 63.8 to 141.9 mW/m^2 [54]. Its similar values, determined by this method, in the Sokoto Basin [8; 38; 55; 56] range from 52.4 to 98.6 mW/m^2.

For the Anambra Basin, the estimated heat flow density varies from 38 to 99 mW/m^2 [57]. For the lower part of the Benue Trough and the adjoining Anambra Basin, it ranges according to Bello and his colleagues [58] from 64.4 to 97.3 mW/m^2 with an average value of 80.1 mW/m^2.

Analysis fulfilled for the Nupe Basin shows that the HFD varies from 30 to 120 mW/m^2 [36]. In the southeastern and southwestern parts of this basin, it is less than 60 mW/m^2, and increases to more than 100 mW/m^2 in its northeastern and northwestern parts. For the Jalingo and environs in the northeastern Nigeria the heat flow is estimated between 53 and 61 mW/m^2 [14; 37].

Heat flow density estimates by this approach fulfilled also for several warm springs of Nigeria. The Ikogosi spring in southwestern part of the country within the Precambrian fractured terrain, where fractured/faulted quartzite may have acted as a conduit for warm groundwater outflow to the surface [59]. Aeromagnetic maps processed on this basis give the heat flow density around 91 mW/m^2. Probably such high heat flow does not concern other parts of the West African Shield, which are at present without HFD determinations within Nigeria. Within the area adjoining the Atlantic shore to the west of Nigeria in the Leo Rise and Dahomeides, the heat flow is 31–33 mW/m^2, which similar to other observations within Precambrian crustal blocks of the world [60].

Conclusions

The heat flow is the most important parameter. It gives the information for studies of lithospheric and crustal dynamics, estimates of promising areas for geothermal energy, understanding of the thermal regime from the point of the hydrocarbons maturity, etc.

A preliminary map of heat flow density for Nigeria was compiled based on accessible determinations in boreholes and estimates derived from analysis of aeromagnetic maps. It varies in a wide range with a contrast pattern in the territory of Nigeria. Activated areas due to rifting are indicated by high heat flow within the eastern part of the Borno Basin, eastern area of the Benue Trough, as well as within the northern part of the Niger Delta, the Sokoto Basin. A high heat flow derived from the spectral analysis of aeromagnetic maps in the vicinity of the Ikogosi hot spring, located in the West Nigerian Shield, require further refinement to trace its margins, as typically rather low heat flow is a specific feature of Precambrian shields.

The high heat flow anomalies (90–100 mW/m^2 and more) could be considered as the most promising parts in the country for detailed investigations as potential sources of geothermal energy, which is suitable to create electric plants mainly based on the binary technology for the production of «geothermal» electricity. Results of geothermal studies within the Niger Delta show that the temperature of 150 °C can be reached in a number of local parts of the area at depth less than 5 km [30] that is suitable to create electric plants based on the binary technology.

It is necessary to stress that high heat flow anomalies could be considered as the most promising parts in the country for detailed investigations as potential sources of geothermal energy [61].

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Received by editorial board 18.06.2019.