Terrestrial heat flow and its role in petroleum geology

E N Osipova[1,3], I V Ivanov[1], V A Smirnov[1] and R N Abramova[2]

[1] Department of Mineral Exploration, Institute of Natural Resources, National Research Tomsk Polytechnic University, 30 Lenin Ave., Tomsk, 634050, Russia
[2] Department of Foreign Language, Institute of Natural Resources, National Research Tomsk Polytechnic University, 30 Lenin Ave., Tomsk, 634050, Russia

E-mail: [3] osipovaen@list.ru

Abstract This paper describes an overview of mineral resources exploration survey by geothermal method based on the studies of terrestrial heat flow, anomalies varying in strike, in depth, physical behavior and in time. Applying geothermometry in oil-gas deposit exploration, based on paleotemperature modeling of sedimentation sequences was illustrated.

1. Introduction

Developed producing fields are gradually being depleted, therefore, the application of highly effective methods in exploring new and new hydrocarbon reservoirs is becoming a topical problem today. Analyzing the numerous hydrocarbon exploration methods, the geothermal method is distinguished based on the study of heat flow emerging from the interior earth to the surface.

The term “geothermal survey” was adopted at the Russian Science and Technology Conference in 1972 (Lvov), where the discussed issues involved effective development of hydrocarbon reservoirs for further exploration drilling. The role of geothermics in studying the Earth energy state is in determining the major theoretical geological problem-evolution of our planet.

Based on today's accumulated actual data, the formation behavior of global, regional and local geotemperature fields have been determined. The theoretical concept in evaluating the formation of geological temperature fields involves the physico-mathematical modeling of heat and mass transfer processes in rocks [1].

2. Heat flow and its role in the formation of interior Earth geothermal fields

Heat flow (q) – heat flows through isothermal surface in unit of time, which, in its turn, depends on the heat nature and source intensity, as well as the heat transfer through rocks exhibiting thermal conductivity through radiation and convection. The sources of heat flow are those processes in Earth interior, as well as solar thermal energy.

Solar activity variations (daily, seasonal, annually) result in cyclic air temperature variations. The longer cycle period, the deeper the thermal exposure. So, daily temperature variations are evident up to 1.5m and are associated with solar heat transfer due to molecular rock thermal conductivity and air convection, water vapors, infiltrated precipitation and underground waters. Seasonal and annual solar activity results in the temperature variations at the depth of 20-40m., where heat transfer is due to molecular thermal conductivity, as well as groundwater flow. The neutral layer is located deeper than 40m, where the temperature is practically stable and is on an average of 3.7 °C higher than the annual average air temperature. Below the neutral layer the temperature is higher than the average

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

temperature up to 3 °C at every 100m. Century climatic changes are reflected in the temperature variations at relatively deep depths. For example, cold and warm spells in the Quaternary period influenced the Earth geotemperature regime at the depth of 3-4km.[2]. As hydrocarbon deposits accumulate lower the neutral layer, then the influence of cyclic solar activity is usually not considered.

Heat flow anomalies are distinguished by four attributes in relation to:

the strike- global, regional, local;

the depth- heat source depth: abyssal (mantle), intermediate (crustal), surface (first lithosphere kilometers);

physical nature- alterations of boundary conditions in time and space and environmental thermal physical properties, thermal conductivity features in media of either heterogeneous thermal conductivity or flowing in a solid body, location pattern of thermal sources and different energy-producing processes;

cycle time- stationary, non-stationary.

Deep (abyssal) thermal processes include radiogenic heat as a result of radiogenic isotope element decay (uranium, thorium, potassium) within rocks. Heat also exerts different processes within the Earth interior. For example, exogenous and endogenous chemical reactions, melting, tide deformation and others. The thermal energy of these sources is significantly higher than the energy in tectonic, seismic and hydrothermal processes [2].

Heat flow from the “solid' Earth interior continuously passes into and disperses in the atmosphere. Heat flow density depends on the thermal-physical properties of the geological environment and is closely associated with the regional tectonic structures, as well as volcanic and hydrothermal activities. The distribution of temperature and its sources in the interior and Earth thermal history are based on the geothermometry information of temperature (t) at different depths, geothermal gradients (G) and flow density (q).

Earth heat flow studies involve information on planetary energy balance, energy of geologic-tectonic processes, thermodynamic conditions within the interior, which, in its turn, could be applied in the exploration and development of mineral resources, as well as exploration of geothermal resources – one of the most potential source of future energy.

3. Application of geothermometry in solving petroleum geology problem-tasks

Investigating the distribution of geothermic temperatures in rocks with different thermal-physical properties is a rather difficult task, however, it is solvable. Modeling provides the solution for both direct thermal conductivity problems (solution in differential equations and single-valued conditions is determined by a temperature field) and reverse problems (to given temperature field the boundary conditions are determined, for example, surface heat exchange coefficient).

Significant geothermal field distortion emerges if the rocks of a disturbing body is by 5-10 times different in thermal conductivity comparable to country rocks. This difference is rare in platform regions [3]. Drilling also influences this temperature balance. Temperature recovery time to initial values is ten-fold higher than the drilling time and depends on drilling method.

The processing of factual basin data revealed that, in many cases, geothermal anomalies are confined to oil-gas deposits. Temperatures in these deposits sometimes exceed background temperatures to 10 ºC or more. Abnormal heat flows showing hydrocarbons could be the result of organic matter catagenesis and hydrocarbon migration. Emerging from greater depths where the temperature is higher, hydrocarbons provide and distribute the heat while heating the rock mass. According to the thermal exposure the oil composition could be indirectly determined – lighter the oil, more intensive the thermal flow [1].

The technique for the exploration of oil-gas-bearing structures by thermo-tomography was already applied in the 20th century; however, it was not perceived as an effective tool in exploration which could have saved million and million dollars [4]. This method includes plotting a 3D model of heat flow and temperature distribution providing possible cross-sections of a geothermal field at any depth, determining favorable level for hydrocarbon formation, as well as predicting oil-gas field distribution

deposit and depth of hydrocarbon accumulations. According to Khutorski this thermo-tomographic model for estimating hydrocarbon potential could be plotted for any territory, and is economically profitable, which, in its turn, shows the advantage of this method.

Other economically effective methods are backstripping and paleotemperature modeling, being based on the geothermal criteria, involve the following: mapping of intensive hydrocarbon generation sources, distribution of relative density of oil resources in oil-gas complex reservoirs, and territorial zoning of potential fields [5]. This method is based on the modeling of heat transmission process in layered sedimentary formation by applying formation temperature measurements, which involved formation temperature measurements and calculated temperatures to vitrinite reflectance.

It is a well-known fact that a sedimentary formation consists of stratigraphic sequences h_i, of which each sequence has given thermal conductivity (λ_i), thermal diffusivity (a_i), heat radiation of radioactive sources (f_i) rocks in sedimentary cross-section and sedimentation time t_i (figure 1).

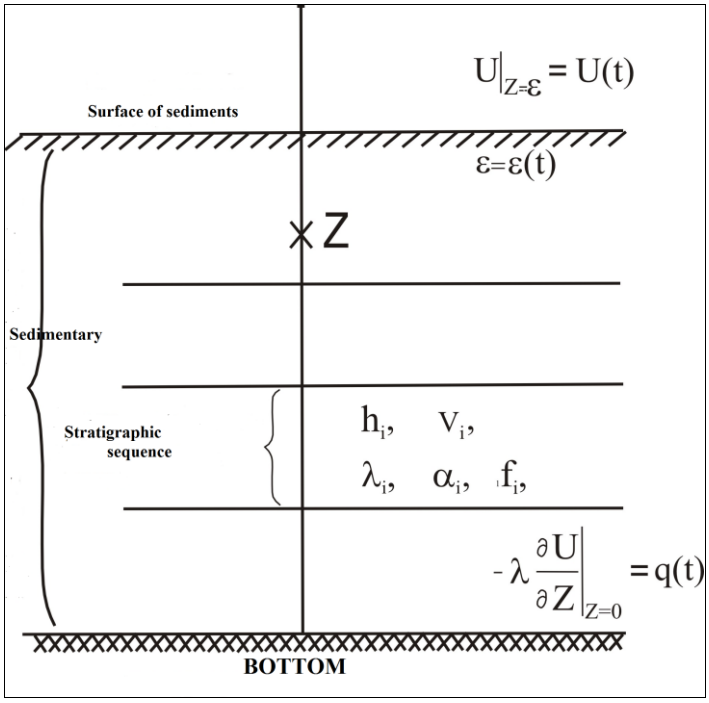

Figure 1. Illustrated scheme of layered sedimentary cross-section in paleotemperature modeling [6]: $\varepsilon = \varepsilon(t)$ – upper boundary of sedimentary thickness; t – sedimentation time; U – temperature; q – hear flow; Z – calculated temperature point; h_i – thickness; v_i – velocity of sedimentation; λ_i – thermal conductivity; a_i – thermal conductivity; f_i – heat radiation density of radioactive sources.

Heat flow from the bottom is determined by geothermic inverse solution. The parameters in modeling paleothermal processes to one well cross-section are depicted in table 1. The values are calculated to 38 deep well cross-sections, drilled in the S-E of Western Siberian platform. This made it possible to identify the distribution of heat flow density within Nurolsk megadepression and its structure contours [5].

Table 1. Example of sedimentary cross-section parameterization, exposed deep well (Vodorasdelnaya 1), determining the parameters of sedimentation and thermo-physical model.

Suite, formation* (stratigraphy)	Thick-ness m*	Age, mil. years	Accumu-lation time mil. years	Density, gr/cm^3	Thermal conducti-vity, W/m·°	T° conducti-vity, m^2/sec.	Heat radiation, W/m^3
Quarternary, *Q*	19	0–1.64	1.64	2.02	1.27	6,5e-007	1.1e-006
Pliocene, N_2	–	1.64–4.71	3.07	–	–	–	–
Miocene, N_1	30	4.71–240.	19.29	2.07	1.31	6,5e-007	1.1e-006
Nekrasov, *nk* Pg_3	168	24.0–32.2	8.3	.	1.35	7e-007	1.2e-006
Cheganian, *g* Pg_{3-2}	50	32.2–41.7	9.4	2.09	1.35	7e-007	1.2e-006
Lulinvorean, *ll* Pg_2	99	41.7–54.8	131	2.09	1.35	7e-007	1.2e-006
Talich, *tl* Pg_1	–	54.8–61.7	6.9	–	–	–	–
Ganlinsk, *gn* Pg_1-K_2	138	61.7–73.2	11.5	2.11	1.37	7e-007	1.25e-006
Slavgorod, *sl* K_2	48	73.2–86.5	13.3	2.11	1.37	7e-007	1.25e-006
Ipatov, *ip* K_2	140	86.5–89.8	3.3	2.18	1.4	7e-007	1.25e-006
Kuznetsov, *kz* K_2	17	89.8–91.6	1.8	2.18	1.43	8e-007	1.25e-006
Pokursk, *pk* K_{1-2}	1057	91.6–114.1	22.5	2.26	1.49	8e-007	1.25e-006
Alymian, a_2K_1	–	114.1–116.3	2.2	–	–	–	–
Alymian, a_1K_1	–	116.3–120.2	3.9	–	–	–	–
Kialinsk, *kls* K_1	459	120.2–132.4	12.2	2.39	1.6	8e-007	1.25e-006
Tarsian, *tr* K_1	93	132.4–136.1	3.7	2.44	1.62	8e-007	1.25e-006
Kulomzian, *klm* K_1	268	136.1–.	9.7	2.44	1.64	8e-007	1.25e-006
Bazhenov, *bg* J_3	26	145.8–151.21	5.4	2.42	1.62	8e-007	1.3e-006
Georgian, *gr* J_3	12	151.2–156.6	5.4	2.42	1.62	8e-007	1.3e.-006
Vasugan, *vs* J_3	62	156.6–162.9	6.3	2.42	1.6	8e-007	1.3e-006
Tumen, *tm* J_{1-2}	313	162.9…	45.1	2.46	1.64	8e-007	1.3e-006

Solving direct geothermic problem-tasks with known value q the temperature U can be calculated in any point of the sedimentary thickness Z within given geological time t.

A geothermal calculation example of one well cross-section is depicted in table 2. Based on the calculated values of 39 deep well cross-sections, maps of geothermal distribution within key geological periods were plotted and intensive intensive hydrocarbon generation sources within Nurolsk megadepression and its structure contours were identified [7, 8].

In early publications, identified intensive hydrocarbon generation sources by geothermal method were described. Comparing the temperatures and time of these sources to Cretaceous and Lower Jurassic oil-gas complex distribution, relative density of generated oil resource distribution was mapped and potential territorial zoning was conducted [9].

Table 2. Thermal history of Bazhenov suite in the sedimentary cross-section of Vodorasdelnaya 1 well.

Suite, formations		Geological age		Surface heat flow and geothermal in suite center (0C) in paleocross-section (m.a)													
		Index	m.a.	0 O	1.64 N_2	4.71 N_1	24.0 Pg_3nk	32.3 $Pg_{3-2}hq$	37.4	41.7 Pg_2ll	54.8 Pg_1tl	61.7 Pg_1-K_2qn	73.2 K_2sl	86.5 K_2ip	89.8 K_2kz	91.6 $K_{1-2}pk$	114.1 K_1a_2
Quarternary		Q	0-1.64	0,3													
Pliocene		N_2	1.64-4.71	0,7	2,6	0,045											
Miocene		N_1	4.71-24.0	1,1	3	4,6	0,045										
Nekrasov		Pg_3h+r	24.0-32.3	4,6	6,7	8,3	7,6	0,045	0,045								
Cheganian		Pg_3r+Pg_2p	32.3-41.7	8,5	10,6	12,2	11,5	10,4	19,9	0,045							
Lulinvorean		Pg_2b+l+i	41.7-54.8	10,9	13,3	14,7	14,1	13	21,6	22	0,045						
Talich		Pg_1t+m	54.8-61.7	12,6	14,8	16,6	15,9	14,8	23,4	23,8	20,5	0,045					
Gankinsk		Pg_1d-K_2m	61.7-73.2	15	17,4	19	18,4	17,3	26	26,2	23	22,1	0,045				
Berezov	Slavgorod	K_2km+st	73,2-86,5	18,4	20,9	22,4	21,6	20,6	29,1	29,5	26,2	25,4	19,9	0,045			
	Ipatov	$K_2st+k+t$	86,5-89,8	21,4	24,1	25,6	24,9	23,8	32,3	32,7	29,4	28,6	23,1	22,2	0,045		
Kuznetsov		K_2t	89.8-91.6	24,1	26,8	28,3	27,7	26,5	35,1	35,4	32,1	31,3	25,9	24,7	20,1	0,045	
Pokrusk		K_2s-K_1al	91.6-114.1	40,9	43,9	45,2	44,7	46,8	52,3	52,6	49,3	48,5	43	41,8	37,3	35,8	0,045
Alymian	Koshaisk member	K_1a	114.1-116.3	57,2	60,6	62	61,3	60,4	69	69,2	65,9	65,1	59,7	58,4	53,9	51,3	21,2
	Layer A	K_1a	116.3-120.2	57,4	60,6	62	61,3	60,4	69	69,2	65,9	65,1	59,7	58,4	53,9	51,3	21,2
Kialinsk		K_1br+q	120.2-132.4	64	67,3	68,8	67,9	67	75,8	75,9	72,6	71,7	66,4	65,1	60,7	58,9	27,9
Tarsian		K_1v	132.4-136.1	71,9	75,2	76,8	75,9	74,9	83,6	83,8	80,5	79,6	74,3	73,1	68,6	65,9	35,8
Kulomzian		K_1v+b	136.1-145.8	76,9	80,2	81,8	81	79,9	88,8	88,9	85,6	84,7	79,4	78,1	73,7	70,9	40,8
Bazhenov		$J_3tt(v)$	145.8-151.2	81	84,4	85,9	85,2	84,1	92,9	93	89,7	88,8	83,5	82,2	77,7	75,1	45
Georgian		J_3km	151.2-156.6	81,6	84,9	86,4	85,7	84,6	93,4	93,5	90,2	89,3	83,9	82,6	78,2	75,6	45,5
Vasugan		J_3 o	156.6-162.9	82,6	86	87,5	86,7	85,7	94,4	94,5	91,3	90,4	85	83,7	79,3	76,6	46,5
Tumen		J_{1-2}	162.9-208.0	87,8	91	92,6	91,8	90,8	99,8	99,7	96,5	95,5	90,3	88,9	84,6	81,8	51,7
Crustal weathering		T-P	208.0-213.0														
Basement		PZ															
Thickness(cross-section),m.			3026	3003	2984	2983	2953	2785	2756,8	2735	2636	2635	2497	2449	2309	2292	1235

4. Conclusion

Deep well drilling is a rather expensive process in exploring the earth interior and results in the destruction of the equilibrium balance of generated formations, which, in its turn, demands significant time for regeneration. Geothermal method is a resource-efficient technique conserving the ecological equilibrium. Potential oil-gas areas could be identified and explored by analyzing the geological structure of this or that area and modeling those heat flow processes within the earth interior. This integrated method makes it possible to determine the density of oil resources in the reservoirs of different oil-gas complexes.

References

[1] A P Kurchikov and B P Stavitskii 1987 *Geotermija neftenosnyh oblastej Zapadnoj Sibiri* 134
[2] Geofizicheskie metody issledovanija zemnoj kory Chapter 5 Termorazvedka http://www.astronet.ru/db/msg/1173309/page47.html
[3] Khutorskoy M D 1982 *Teplovoj potok v oblastjah strukturno-geologicheskih neodnorodnostej* (Moscow: Nauka)
[4] Nauka i tehnologii Rossii: Rossijskie uchenye nashli deshevyj sposob poiska nefti http://strf.ru/material.aspx?CatalogId=21731&d_no=43623#.VXA2a9LtlBc
[5] Isaev V I, Lobova G A and Osipova E N 2014 The oil and gas contents of the Lower Jurassic and Achimovka reservoirs of the Nyurol`ka megadepression *Russian Geology and Geophysics* **55** 1418–28
[6] Gulenok R Yu, Isaev V I, Kosygin V Yu, Lobova G A and Starostenko V I 2011 Estimation of the Oil-and-Gas Potential of Sedimentary Depression in the Far East and West Siberia Based on Gravimetry and Geothermy Data *Russian Journal of Pacific Geology* **5**(4) 273–87
[7] Osipova E N, Prakoyo F S and Kudryashova L K 2014 Petroleum potential of the Neocomian deposit of Nyurolsky megadepression *IOP Conf. Ser.: Earth Environ. Sci.* **21** 0120011
[8] Lobova G, Osipova E, Isaev V and Terre D 2014 Petroleum potential of Lower-Jurassic deposits in Nurolsk megadepression. Scientific and Technical Challenges in the Well Drilling *IOP Conf. Ser.: Earth Environ. Sci.* **21** 012001

[9] Lobova G A, Popov S A and Fomin A N 2013 Lokalizacija prognoznyh resursov nefti jursko-melovyh neftegazonosnyh kompleksov Ust'-Tymskoj megavpadiny *Neftjanoe hozjajstvo* **2** 36–40