226

ons with

.e solubility of hydro-
nperature up to a spe-
The decrease might be
of equilibrium towards
note that the true solu-
eases with tempera-
mount of hydrocarbons
plex will be still less
solubility of petroleum
ts were performed on
of a model bed, bent
n glass jackets [model
ets enabled us to create
anticlines" of the bed.

ed solution of Markov
point 250°C) in a solu-
e versions of the ex-
1) in the first anti-
0°C, in the second
e the temperature
C; 3) in the first
as 95°C, in the second
the current was
low velocity was ad-
nperature in the sec-
n of the experiment.
observed in the first
third.

d that transport of
dal solutions contain-
ible only in a limited
uid passes outside the
ature isotherms, ow-
ure, the oil separates
an independent phase.

CES

tseva, M.A., 1947,
no. 69.

Kolloidn. zhurn.,

ov, Ye. I., 1965,
eofiz., no. 2.

CHEMISTRY OF
w.

, L. Ye., and Gont-
IBLE MECHANISM
IL DEPOSITS FROM
NS IN A PRODUC-
SYSTEM: In ORI-
Nedra Press.

olloidn. zhur.,

ova, G.P., and
953, Ukr. khim.

IGR/nb

GL03533

Geothermy of Lake Baykal region

S.V. Lysak

Geothermal measurements in the Lake Baykal region were begun in 1953. Temperature measurements, made previously in shallow boreholes and mine workings and still being made, characterize only the zone of environmental effects and the temperature of permanently frozen rocks; they may therefore be used only for description of the temperature of the heliothermozone, which at large depths below the surface is colder because of cyclic changes in solar irradiation. Our task was to establish the temperature conditions of deeper crustal layers—the layers of the geothermozone in which the temperature invariably rises with depth; this increase indicates a flow of heat from the center of the earth to the surface.

The geothermozone has now been revealed in the Lake Baykal region by 10 deep wells sunk in the intermontane depressions.[1]

The increase of temperature with depths in the wells is described by curves which have almost the same slopes throughout their extent. However, the temperatures at the same depths vary from depression to depression and within the same depression, due to the geological structure of the depressions and most of all to the thermophysical properties of the rocks forming their sedimentary mantle.

Depressions of the Baykal type are filled with Neogene and Quaternary sand and clay deposits, sometimes parted by basalt, basaltic tuff and tuffaceous sandstone (Tunkinskiy basin) or by sand and gravel deposits (Selenga depression). Depressions of the Transbaykalian type are characterized by effusive-sedimentary, frequently coal-bearing formations of the Lower Cretaceous and Middle Jurassic (Borgoyskaya basin). The rocks of the sedimentary mantles of the depressions have large specific heat resistances ranging from 0.33-0.91 m hr deg C/kcal in sandstone to 2.94-3.33 in sand, and even to 4.85 in clay.[2] These large specific resistences of rocks lead to very high rates of increase of temperature with depth.

Geothermal gradients in the Quaternary deposits forming the upper part of the sedimentary mantle in depressions of the Baykalian type vary between 38 and 126 m/deg C. The maximum values are characteristic of Tunkinskiy no. 2 well (126 m/deg) and Barguzin no. 1 well (84 m/deg) where the rocks are frozen to considerable depths from the surface. In the Selenga depression the geothermal gradients range from 50 to 38 m/deg, averaging 47 m/deg. The geothermal gradients are slightly lower in Neogene deposits (to 67/30 m/deg, averaging 45 m/deg), with the lowest values characteristic of the Tunkinskiy no. 2 well (40 m/deg) and Barguzin no. 1 well (30 m/deg).

It is very difficult to explain the differences between the geothermal gradients in the Quaternary and Neogene deposits, in view of their very similar lithological composition; it will therefore be more correct to analyze the geothermal characteristics of individual lithofacies of Cenozoic deposits, rather than the characteristics of age categories.

In the Selenga depression the largest geothermal gradients are characteristic of the sand and gritstone rocks, in which they reach 43 m/deg (Istok no. 1 well) and even 62 m/deg (Tvorogovo no. 1 well). In the siltstone and sandstone deposits the geothermal gradients drop from 54-37 m/deg (Tvorogovo no. 1 well) to 32 m/deg (Istok no. 1 well). The smallest gradients (31 m/deg) were calculated for clays and clay shales. A reduction in the geothermal gradient corresponds to an increase in the density of the rocks, since the lowest density of rocks in the Selenga depression, according to the data of K.A. Savinskiy et al. (6), is characteristic of the sand and gravel deposits (1.5-1.6 g/cc) and the density of compact siltstone increases to 2.15-2.22 g/cc.

In Tunkinskiy no. 2 well, the key well for the geological section of sedimentary deposits of the Tunkinskiy basin, geothermal gradients range from 120 m/deg (in recent sand and shingle deposits) to 31 m/deg (in Miocene sand and clay deposits). The values of the gradients vary even more widely for lithologically different rock units (from 143 to 28 m/deg). The highest gradients are characteristic of the upper part of the section (to a depth of 700 m) and they are particularly large in the range of 430-720 m, where permanently frozen rocks were found in the course of drilling.

Translated from Geotermiya Pribaykal'ya, Geologiya i Geofizika, 1968, no. 9, p.16-21. The author is with the Institute of the Earth's Crust, Siberian Department, USSR Academy of Sciences, Irkutsk.

[1] Temperatures in the wells were measured with quick-response electric thermometers. Periods during which the wells were empty (before thermal logging operations in them were started) varied between 11 days (Stephaya no.1 well) to 48 days (Istok no.1 well) and averaged 25 days. Operations were carried out by workers of the Eastern Geophysical Trust; thermograms were worked up by S.V. Lysak.

[2] Data on thermal properties of the rocks are given by analogy with existing coefficients.

When the well was driven further and during later tests, the permanently frozen rocks thawed within the range of the heat conductance from the well shaft, and no negative temperatures were recorded in this range on the thermal logging diagram. It should be noted that considerable heating of the well shaft is also indicated by the higher temperatures near the well head (11.5°C at a depth of 70 m). The temperature increases very slowly to a depth of 720 m (on average, 0.83 0.83°C/100 m), but at greater depths the temperature increases far more rapidly 2.8°C/ 100 m).

The minimum geothermal gradients are noted in sand, and sand and siltstone units (22-26 m/deg); the gradients increase to 42-54 m/deg in clay sands containing basalt partings. The temperature measurements clearly reveal large monolithic basalt bodies in which the geothermal gradients are always higher than in the enclosing sedimentary rocks.

According to data from Barguzin no. 1 well, geothermal gradients in the Barguzin basin range from 84 m/deg (sand suite) to 22 m/deg (coal-bearing suite), gradually decreasing with depth. Variations in geothermal gradients are even more considerable in lithologically different rock units - from 120 to 13 m/deg. In the upper part of the section on the Barguzin well, where frozen rock layers 300-400 m thick were recorded at a depth of 117 m during drilling (7), the geothermal gradients are highest - from 46 m/deg in sand and clay deposits to 120 m/deg in gritstone. The gradients decrease with depth. The minimum geothermal gradients are characteristic of clay shales (13 m/deg) and coaly shales (18 m/deg) and also of argillaceous sandstone (28-37m/deg), while the maximum gradients are characteristic of sandy clays (41 m/deg) and inequigranular sands containing shingle and igneous rock gravel (66 m/deg).

Only one of the many basins of the Transbaykalian type, namely the Borgoyskaya basin, has been studied from the geothermal standpoint. According to data from Stepnaya no. 1 well, the lowest geothermal gradients are characteristic of deposits of the Lake Gusinoye suite (Cr_1); the highest are characteristic of the Borgoyskaya suite (J_3). The gradients decrease in the sand and siltstone (to 38 m/deg) and increase in the tuffaceous and clastic rocks (to 44-54 m/deg).

A definite relationship is therefore noted in basins of both Baykalian and Transbaykalian type between the distribution of temperatures at depth and the lithological composition of constituent deposits of the basins. The highest geothermal gradients are characteristic of gravel and shingle deposits and inequigranular sand (especially frozen), and also of basalt and tuffs and clastic rocks. The lowest gradients are characteristic of sand and clay deposits.

The geothermal conditions in the intermontane depressions depend on the structure of a given depression, as well as on the composition of the constituent rocks. Geothermal parameters of the depressions are governed by a combination of these conditions. We shall therefore consider in somewhat greater detail the overall geothermal characteristics of individual depressions.

TUNKINSKIY BASIN

The geothermal conditions of the Tunkinskiy basin can be characterized by temperature measurements from two deep wells; data from Tunkinskiy no. 2 well, where the geothermal gradient was determined, were taken as the basis of our interpretation.

Despite the considerable thickness of the permanently frozen rocks in the basin, the temperatures below the base of the permafrost increase fairly rapidly. The frozen rocks apparently act as a kind of screen for the heat ascending from the depths.

The crystalline basement of the basin is a deep, asymetrical trough of practically latitudinal strike formed in the Cenozoic along the zone of an old fault (8). The main depths of the trough, 2-3 km, are displaced to the eastern margin of the basin.

At the surface of the crystalline basement, the minimum temperatures are probably in the southern and southwestern parts of the basin, where they barely exceed 20°C. In the central part of the basin and especially in the region of the greatest subsidence, temperatures increase to 50-75°C or more.

Temperatures at the basement surface are not solely dependent on its depth. This is illustrated by the Tunkinskiy no. 1 well, in which a temperature of 52.8°C was recorded at the basement surface (1000 m depth), that is, practically the same temperature as was recorded in Tunkinskiy no. 2 well at 2000 m. The high temperatures in this well were apparently due to a flow of heat from depths along a fault zone in the basement, as confirmed by the presence of gushing hot springs.

To judge by the thermal logging data for Tunkinskiy no. 1 well, the temperature increases very rapidly with depth in zones of open faults, since the geothermal gradient is 23 m/deg (over the depth range in which the well was investigated) but falls to 19 m/deg at depths of more than 500 m, which is only half the geothermal gradient in the Tunkinskiy no. 2 well. Similar variation is exhibited by other geothermal parameters, especially the heat flux density.

The heat flow in the Tunkinskiy basin may be roughly determined from the tabulated values of the specific heat resistances of the rocks (1, 3) and mean geothermal gradients computed from actual temperature measurements in the wells. Along the section it increases from 1.10 x 10^{-6} cal/cm^2 sec (in basalt) to 1.94 x 10^{-6} cal/cm^2 sec or more (in sand and sandstone).

Monolithic and compact basalt are poor conductors of heat from the depths to the surface. Therefore the low heat flow in the region of maximum subsidence of the basement, where basalt is most prevalent, probably favors the preservation of the thick strata of permanently frozen rocks.

In the central part of the Tunkinskiy basin the heat flow increases to 1.33 x 10^{-6} cal/cm^2/sec and reaches 2.66 x 10^{-6} cal/cm^2 sec in fault zones.

SELENGA DEPRESSION

The Selenga depression is a tectonic structure complicating the southwestern limb of the Baykal basin and consisting of a downwarped area filled with a thick mass of Cenozoic rocks (2). The thickness of the sedimentary mantle increases towards the shores of Lake Baykal, where it is 5 km or more.

In the roof of the Precambrian basement in the Selenga depression, the temperature has been measured directly only in Tvorogovo no. 1 well; in the remaining wells it has been calculated by extrapolation. In the areas investigated, the temperatures at the basement surface range from 37°C (Tvorogovo no. 1 well at a depth of 1800 m) to 80-90° (Istok well at depths of 2800-3000 m). In geological structures where the depth to basement is very considerable (Istok uplift – 3500 m, Del'tovyy trough – 5000 m), the temperatures at the basement surface exceed 100°C. Temperatures are particularly high in the fault zone of the Istok uplift. There the temperature exceeds 60°C at a depth of 2000 m, while in Istok no. 3 well, which directly enters the fault zone, the temperature at 2500 m reaches 90°C.

Several temperature zones may be distinguished on the basement surface of the Selenga depression on the basis of the position of the isotherms. The temperature does not exceed 20°C on the marginal outcrops of the basement (Khamar-Daban and Morskoy ranges), or on the raised southeastern marginal part of the depression. On the slopes of the depression and in the southeastern part of the Tvorogovo-Istok uplift, the temperature increases to 20-50°C. In the southeastern part of the Del'tovyy trough, in the southwestern part of the Yuzhnyy trough and throughout the greater part of the area of the Tvorogovo-Istok uplift the temperature reaches 50-75°C. On the shores of Lake Baykal, where the rocks of the crystalline basement plunge to a depth of 3-5 km, the temperature increases to 75-100°C or more.

The available geothermal information on the Selenga depression gives some idea of the values of the main geothermal parameters of its sedimentary mantle.

The highest geothermal gradients (60 m/deg) are characteristic of the slopes of the depression, which are filled with coarse-grained sand and gritstone deposits. The roughly estimated heat flow here does not exceed 0.88 x 10^{-6} cal/cm^2 sec. On the Tvorogovo uplift, and especially in the Yuzhnyy and Del'tovyy troughs, the geothermal gradients decrease to 52-41 m/deg, owing to the presence of a large amount of sand and clay. The heat flow increases in these areas to 1.26 x 10^{-6} cal/cm^2 sec. On the Istok uplift the geothermal gradient is 32 m/deg and the heat flow reaches 1.77 x 10^{-6} cal/cm^2 sec.

According to the data of Ye A. Lyubimova and V.A. Shelyagin (5), there is a thermal anomaly beneath the floor of Lake Baykal, characterized by a higher heat flow which reaches 3.2 x 10^{-6} cal/cm^2 sec. The heat flow is, however, greatly reduced by the cold water of the lake (a 7% reduction) and by the growing layer of sediments, brought in mainly by the Selenga river, which absorbs part of the heat (a 30% reduction). Consequently, even without other corrections (the effect of irregularities of relief and glaciation), the mean heat flow should not exceed 2.0 x 10^{-6} cal/cm^2 sec in the Selenga depression. According to our data, the roughly estimated heat flow is 1.5 x 10^{-6} cal/cm^2 sec.

BARGUZIN BASIN

Geothermal information on Barguzin basin was obtained from only one well near the village of Mogoyto, where the basement is 1402 m deep. It may be assumed from the geothermal characteristics of the section of this well that temperature at the roof of the basement there reaches 40.3°C.

The following geothermal zones can be distinguished on the surface of the basement in the basin: 0-20°C – the marginal outcrops of the basement comprising Barguzin and Ikatshiy ranges and their spurs (Ulyun, Sakhulinskiy, and others), and also the underground continuations of these projections; 20-50°C - the central and northern parts of the basin, the regions of recent deposits and uplifts (kuytuns); 50-75°C - downwarpings of the basement in the western part of the basin – Yuzhno-Dzhidakan, Ust'-Minday and others; more than 75°C – Argodinsk trough.

The mean geothermal gradient in the sedimentary mantle of Barguzin basin is 28 m/deg at a depth of 500 m or more. The roughly estimated heat flow in the vertical section of the sedimentary mantle increases from 0.72 x 10^{-6} cal/cm^2 sec (in sandy clay) to 2.80 x 10^{-6} cal/cm^2 sec (in clay shales and coaly shales); the average for the basin as a whole exceeds 2.0 x 10^{-6} cal/cm^2 sec, making it considerably higher than in the other basins of the Baykal type (Selenga and Tunginskiy).

The higher heat flow in this basin is apparently also characteristic of open fault zones in the area of Ulyun, the Garga, the Alla and other rivers, where many hot water springs are known.

Geothermal conditions in the major intermontane depressions of the Lake Baykal region can therefore be approximately described on the basis of the available and as yet sparse records of deep temperature measurements.

Geothermal measurements have not been made in the mountain ranges in eastern Siberia, and the few measurements made in shallow wells and mine workings characterize only the zone of environmental influences and the temperatures of permanently frozen rocks. These mountain and folded structures, which arose in the Precambrian and consist of Archean and Proterozoic metamorphic and igneous rocks, are regions of higher radiant emission and of cooling by water and air. The geothermal gradient therefore scarcely exceeds 1°/100 m. This gradient is confirmed both by comparison with similar regions in the Soviet Union (the Kola peninsula and elsewhere) and by gradients calculated by us for the crystalline basement rocks of the Irkutsk amphitheater (4).

Below the zone of cooling, which is over 1.5-2 km in the mountain ranges, there are complicated systems of thermal waters which emerge at the surface only along major open faults, as hot springs. The points at which these waters emerge at the surface are directly related to zones of large young faults which are the structural limits between rigid uplifted rock masses and the relatively more mobile submerged blocks on which intermontane depressions of the Baykal type were formed. Further study of the geothermal regime will make it possible to describe the heat flow in these tectonically interesting regions, since heat is one of the main causes, or to be more precise, the energy factor involved in many tectonic and other endogenous processes, it is difficult or impossible

causes, or to be more precise; the energy factor involved in many tectonic and other endogenous processes; it is difficult or impossible to understand their origin without clarifying the principal causes.

REFERENCES

1. Dyakonov, D.I., 1958, GEOTHERMY IN PETROLEUM GEOLOGY: Gostoptekhizdat.

2. Zamarayev, S.M., and Samsonov, V.V., 1959, GEOLOGICAL STRUCTURE AND OIL AND GAS CONTENT OF SELENGA DEPRESSION. GEOLOGY AND OIL AND GAS CONTENT OF EASTERN SIBERIA: Moscow, Gostoptekhizdat.

3. Kobranova, V.N., 1962, PHYSICAL PROPERTIES OF ROCKS: Moscow, Gostoptekhizdat.

4. Lysak, S.V., 1965, GEOTHERMAL CONDITIONS AND THERMAL WATERS OF SOUTHERN PART OF EASTERN SIBERIA: Author's abstract of thesis, Irkutsk.

5. Lyubimova, Ye. A., and Shelyagin, V.A., 1966, HEAT FLOW THROUGH FLOOR OF LAKE BAYKAL: Dokl. AN SSSR, v. 171, no. 6.

6. Savinskiy, K.A., Mandel'baum, M. M., Troitskiy, V.N., Shekht, N.I., and D'yachkov, N., 1959, EFFICIENCY OF GEOPHYSICAL METHODS OF PROSPECTING IN SOUTHERN PART OF SIBERIAN PLATFORM, BASINS OF TRANSBAYKALIA AND THE FAR EAST: Moscow, Gostoptekhizdat.

7. Solonenko, V.P., 1960, STUDIES ON ENGINEERING GEOLOGY OF EASTERN SIBERIA: Irkutsk.

8. Florensov, N.A., 1960, MESOZOIC AND CENOZOIC BASINS OF PRIBAYKALIA: Moscow, Leningrad, Izd-vo AN SSSR.

IGR/nb

Princ

Along with the de
principle and the imp
of metamorphic facie
in the study of region
taking form in the lit
the identification of
and of metamorphic
ferent approaches to
noted.

1. Identification
phism" and types of
plexes on the basis o
eralogical) features,
ferences in pressure
ple, A. Miyashiro (1
types of metamorphis
kyanite-sillimanite a
and three correspon
Rioke-Abakuma, Bar
A similar approach i
Zwart and others (22
hypothetical differenc
dients. The combina
of pressure has also
writers (4, 3) in dis
"high-pressure zones
complexes" and also
("homogeneously me
extent.

2. Identification
tions by geochemical
shev (7), in particula
tionship of potassium
has distinguished two
he believes are of re
authors have also not
ization of different m
6, 8).

3. Identification
by the ascertainable c
(9), or by the compos
primary-sedimentary
tions – that is, the re
mentary formations"

Translated from Printsip
regional'no-metamorfich
i Geofizika, 1969, no. 3
with the Institute of Geo
Academy of Sciences, S

[1]The term "regional met
present writers only in th
(regional) occurrence, in
morphism.