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RELATIONSHIP BETWEEN HEAT FLOWS AND GEOLOGICAL STRUCTURES IN THE SICHUAN BASIN, P.R. CHINA

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SUMMARY - Based on an extensive data collection and analysis, this research has provided reliable representations of the features of the geothermal fields, their heat flow, and relationships with geological structures in the Sichuan Basin. The isotherms below a depth of 1,000 m show high values in the Central Uplift and the Southwest Uplift, and low values in the Northwest and Southeast Depressions. These features probably indicate undulation of crystalline basement and structural depression. At depths greater than 3,000 m, the isotherms tend to become simpler and regionalized. The mean heat flow in the basin is 69.1 mW/m^2 . In the Central Uplift, the Northwest Depression and the East of the basin, heat-flow values range from 58.6 to 71.2 mW/m^2 , with a mean value of 66.1 mW/m^2 . In the south and southwest, it varies from 76.6 to 100.5 mW/m^2 , with a mean value of 86.2 mW/m^2 . High heat-flow values occur within the uplift of the crystalline basement in the southwest Sichuan, and the heat flow decreases from the south, through the central area, to the northwest.

1. INTRODUCTION

The Sichuan Basin is a large scale hydrocarbon-bearing basin with an area of $180,000 \text{ km}^2$. Since the 1950's, much oil exploration and production activity has been carried out. Data collection has been mainly from the northwestern central, eastern, southern and southwestern parts of the basin, including temperature loggings from more than 1,300 wells (continuous temperature loggings from 154 wells), and includes the gathering of 138 core samples. These data can be taken as characterising the whole basin. All of the well temperature data were pre-treated and corrected before being used for analysis. 117 core samples were measured for thermal conductivity using the divided bar. The radioactive content of the rocks was measured by neutron activation analysis of 25 core samples.

2. REGIONAL GEOLOGY AND STRUCTURE

The Sichuan Basin belongs to a sub-structure of the Yangtze Para-platform. It has been a region of tectonism through the Mesozoic to the Cenozoic Eras. Although there were some lacuna caused by uplift or erosion, this was mainly a subsidence region, and formed as a large scale sedimentary basin since the Cambrian. The well-developed marine facies of the Cambrian, Mesozoic, Lower and Middle Triassic strata are overlain on the Pre-Cambrian folded base. From the Upper Triassic to the Early Tertiary, continental deposits dominated the strata. The whole basin was folded by the Himalayan Movement which produced the current structure of the basin. Three structural zones make up the basin: the Northwest Depression, the Central Uplift and the

Southeast Folded Belt (Fig. 1). They are surrounded by Mt. Longmen to the west and northwest, Mt. Daba to the northeast, Mt. Huaying to the east, and Mt. Qiyao to the south.

2.1 The Northwest Depression

The Northwest Depression was dominated by Mesozoic to Cenozoic deposits and located to the west of the Mt. Longquan Anticline and to the north of Mt. Yin. The western portion is called the Chengdu Depression, and the northern portion is called the Zitong-Tongjiang Depression. To the southeast, it gradually becomes to the Central Uplift. Geophysical data indicate that the crystalline basement lies 6 - 11 km deep (Fig. 2), overlain by about 6,000 m of Mesozoic and Cenozoic continental sedimentary deposits.

2.2 The Central Uplift

The Central Uplift is located between the east of Mt. Longquan and the west of Mt. Huaying, where large areas of Jurassic red strata have outcropped. Based on its development and features, the regional geological structure can be divided into three sub-structural units: the Weiyuan-Longnusi Uplift, the Nanchong Incline, and the Ziliujing Depression. The crystalline basement was uplifted during the Weiyuan-Longnusi Uplift, and is buried about 4 km deep. The Longnusi Structure is buried about 6 km deep (Fig. 2).

2.3 The Southeast Folded Belt

This folded belt lies between Mts. Huaying and Qiyao. It

Fig. 1 Regional Geological Structure of the Sichuan Basin

- (1) East highly folded belt. (2) South lowly folded belt.
 (3) Zhulijing Depression. (4) Wei yuan-Longnushi Uplift.
 (5) Nanchong Slope. (6) Tongjiang Depression.
 (7) Chengdu Depression.

Fig. 2 Burial Depth of the Crystalline Basement in the Sichuan Basin

The result is derived from aeromagnetic data. Positive and negative signs represent magnetic anomalies. Intervals are in km.

is located in the western incline of the Ei-Xiang-Qian Depression. Due to the uplift of the Eastern Jiangnan Palaeo-continental which began in the Jurassic, it has developed as a depression. The depth of the crystalline basement is between 7 and 9 km, and over 10 km in places. Based on its different structural features, it can be divided into two sub-units: a high folded belt in the East Sichuan, and a folded belt in the South Sichuan. The former is located to the east of Mt. Huaying and Shilongxiao, and to the west of Mt. Qiyao. It is a recurrently folded area, dominated by high anticlines and controlled by large scale faults. The latter is located to the west of the former.

3. MAIN FEATURES OF THE REGIONAL GEOTHERMAL FIELD

3.1 Earth Temperature Data

3.1.1 Continuous Temperature Measurements from Drill Holes

A total of 128 wells were used for analysis of the geothermal fields. Data from 72 wells included steady-state temperature measurements. 24 wells were used for temperature gradient measurement and 48 were measured at an early stage of oil production. In general, the data are of good quality because of a long period of well shut-down (more than 15 days) and the steady-state of the wells. In addition, these data were almost evenly distributed over the study area, and temperature data of comprehensive loggings from 56 wells were also used for the study. The data from the shorter-period of well shut-down (usually 1 - 2 days) were used for statistical analysis in order to obtain the steady-state temperature.

The continuous temperature loggings were normally measured at depths between 1,000 m and 4,000 m, and the deepest at 7,000m (Well Guanji). The mainstrata involved were from the Jurassic, Triassic and Permian periods. For the whole basin, temperature measurements were made in strata from the Pre-Cambrian, through to Cretaceous. For example, in well Wei-15, temperature measurements were made for the Pre-Cambrian strata, which has assisted in our understanding of temperature variations through a wide range of strata.

3.1.2 Steady-State Temperature of Oil/Gas Layers

Steady-state temperature values of the oil/gas layers were measured in the middle layers of the oil/gas reservoirs, where the well section had been shut down and the pressure stable for 8 to 12 hours. During this study, 196 static temperature data were selected from 89 wells, at depths from 1,000 m to 5,500 m. They were distributed evenly over the whole study area. Most of measurement were repeated several times, producing identical values.

3.1.3. Earth Temperature and Depth of the Isothermal Belt

The depth of the isothermal belt is defined as $Z_y = 19.1Z_i$, where Z_i is the mean depth at which daily temperatures were measured. According to data from the Sichuan Meteorological Observatory, Z_i is approximately equal to 1.0 m. Therefore, the depth of the isothermal belt for a single year is about 20 m. In the light of historical temperature readings from the Sichuan Meteorological Observatory, the average air temperature is 16° C in the northwest of Sichuan, 20° C in the east, and in the rest of the region it is 18° C. Considering the relationship between the mean air temperature and the isothermal belt temperature, 18° C, 22° C and 20° C were estimated as the temperatures of the isothermal belt for the northwest, the east and the rest of the basin.

3.2 Earth Temperature Distribution and Influencing Factors

Within a few kilometres depth of the shallow crust, earth temperature could be affected by the topography of the crystalline basement, the shape of its structural features, and the activity of ground water and magma. It is also related to the occurrence of oil/gas fluid in drill holes. Based on data analysis of the basin, the main influence is the crystalline basement topography and the shape of structural undulation. Oil/gas fluid has a limited effect on some layers only. Ground water and magma activity is strong in the outer basin, but weak in most of the inner basin areas. From regional analysis of the earth temperature in the basin, the effects of ground water or oil/gas fluid can be minimized. Comparing the isotherms (Fig. 4) with the buried depth of the crystalline basement (Fig. 2), at a depth of 2,500 m a positive correlation between earth temperature and topography of the crystalline basement was revealed. High earth temperatures occur at the Weiyuan-Longnushi Uplift, and low temperatures at the East and Northwest Depressions. This temperature pattern is probably caused by highly conductive crystalline material which is overlain by sedimentary rocks. High heat flow could be trapped near the boundary between the uplifted crystalline and low conductivity sediments, causing heat flow to be refracted and re-distributed.

3.3 Features of the Earth Temperature Field

Figs. 3 to 5 show the regional isotherms at different depths (1,000 to 6,000 m) based on continuous temperature measurements from 128 wells throughout the whole basin. They show the variations of the earth temperature field in both the horizontal and vertical.

3.3.1 Lateral Distribution of Temperature Features

Figs. 3 and 5 show high values in the Central Uplift, and

Fig. 3 Geoisotherms ($^{\circ}\text{C}$) at a Depth of 1000 m in the Sichuan Basin

Fig. 4 Geoisotherms ($^{\circ}\text{C}$) at a Depth of 2500 m in the Sichuan Basin

low values in the Northwest and Southeast Depressions. Temperatures slowly increase from the Northwest Depression to the Central Uplift, and quickly rise from the East Depression to the Central Uplift with densely distributed isotherms. This feature perhaps reflects crystalline basement being uplifted slowly from the northwest to the central area, and quickly uplifted from the Southeast Depression to the central area through the Mt. Huaying fracture zone.

In the Central Uplift, the general trend of the isotherms is northeast to southwest (Fig. 5), which is coincident with the axis of the Weiyuan-Longnusi Uplift. Figs. 3 and 4 show high earth temperatures in the west of Shuining, which accords with the uplift of the Xiangshan crystalline basement (Fig. 2). The high temperature zone between Wusheng and Shuining is perfectly accordant with the Longnusi-Guangan crystalline basement uplift. To the west of Shuining, there is a low temperature area which could represent a depression. It should be noted that the maximum earth temperature in the basin is not found on the highest position of the crystalline basement uplift of the Weiyuan Anticline, but on the Ziliujing Depression, near Weiyuan. This is probably due to the secular degradation, and poor quality, of heat preservation of the exposed Weiyuan Anticline.

In the Northwest Depression, a relatively high temperature zone within Wangchang, Langzhong, Zitong and Mianyang divides the northwest part into three low temperature areas. The low temperature area in the east coincides with the North Depression, and the southwest low temperature area relates to the Chengdu Depression; the northwest low temperature area reflects the Zitong Syncline (although imperfectly); the high temperature zone coincides with the saddle of the crystalline basement uplift, which is connected to the three depressions.

In the folded area of the Southeast Depression, earth temperatures decrease from northwest to southeast, which reflects the existence of the Central Uplift and the structural trend from NE to SW. The high earth temperature zone near Luzhou indicates the existence of the Luzhou Palaeo-Uplift. The low temperature contour of the area to the west of Dianjiang are oriented southward from the Liangping Syncline. This may indicate that the Liangping Syncline extends further south.

3.3.2. Vertical Features

With increasing depth, the isotherms change from complex multi-centres to simple flat shapes. The basic features of the isotherms between the depths of 1,000 m and 2,500 m are similar (Figs. 3 and 4). These features can be used to analyse the geological sub-structures affected by the topography of the crystalline basement. For example, the three low temperature areas in the northwest correspond to the North Depression, the Chengdu

Depression and the Zitong Syncline. The high temperature area suggests the uplift area connecting with the three depressions. This feature represents the complex fluctuation structure influenced by the epi-structural movement of the upper part. At depths greater than 2,500 m, the isotherms tend to simplify and become regionalized, since the temperatures have been strongly influenced by the structural shape and topography of the basement. The isotherms at 6,000 m show the three major structural features: the Northwest Depression, the Central Uplift and the East Depression Belt (Fig. 5). Therefore, some features which were shown on the isotherms for above 2,500 m do not appear, but tend to be exposed regionally at greater depths. For example, the three depressions (saddle structures) which appear in the isotherms of the northwest region at shallow depths, are weakly present at the greater depths (over 2,500 m). Several structures in the Central Uplift can only be shown as two large scale structural units in Weiyuan and Shuining (Fig. 5).

4. ANALYSIS OF TERRESTRIAL HEAT FLOW

4.1 Calculation of Heat Flow Values

4.1.1 Temperature

Data used for heat flow calculation were measured in the steady-state wells at an early stage of oil production. As many well-bottom temperatures as possible, and temperatures from the deep wells, were used for heat flow calculation. The major features of the temperature data are: (1) gentle slope of the temperature versus depth curves, with little disturbance; (2) near surface temperatures are close to that of the isothermal belt; (3) similar temperature variations appear in different wells at the same structural locations; (4) no significant difference for heat-flow values calculated for the same well, but at different depths; (5) temperatures near the bottom of wells did not show significant changes;

4.1.2 Thermal Conductivity of the Rocks

117 core samples were collected covering all stratigraphic sequences, throughout the whole basin for measurements of thermal conductivity. These rocks display strong diagenesis with low porosity (usually <5%), and there is an insignificant difference in thermal conductivity between dry samples and water-saturated samples. Based on these measurements, and another 187 thermal conductivities from a previous study of the basin, the average thermal conductivities of the strata were calculated using the equation:

$$\kappa = D \left(\frac{d_1}{k_1} + \frac{d_2}{k_2} + \dots + \frac{d_n}{k_n} \right)^{-1}$$

Here, $k_1, k_2, \dots, k_n$ are the mean thermal conductivities

Fig. 5 Geoisotherms ($^{\circ}\text{C}$) at a Depth of 6000 m in the Sichuan Basin

Fig. 6 Heat Flow Distribution in the Sichuan Basin

for lithologies; $d_1, d_2, \dots, d_n$ are the accumulated thicknesses for the lithologies, and $D = d_1 + d_2 + \dots + d_n$.

4.1.3 Heat Flow Calculations

For those wells with steady-state temperature measurements, but without lithological descriptions, thermal conductivities could not be obtained only from the core samples. In this situation, the regional mean values of thermal conductivity were used for heat flow calculation rather than well location values. The whole study area was divided into different sections, and all sub-areas within each section possess similar geological structures. For each section, the average thermal conductivity was calculated for each different lithology section. It is assumed that physical features of the same rock type in similar geological structures will not show significant variations in thermal conductivity. Therefore, heat-flow values derived from regional mean values of thermal conductivity were acceptable, although these values might not be calculated directly from the oil well data.

The average value of heat flow is defined as the arithmetic mean of the calculated and estimated heat flow values. In the Sichuan Basin, the average values are 69.1, 64.1, 65.7, 70.7, 75.8 and 95.9 mW/m^2 for the east, northwest, central, south and southwest regions respectively.

4.2 Heat-Flow Distribution and Geological Interpretation

The heat-flow distribution of the Sichuan Basin is shown in Fig. 6. The high heat-flow values lie within the uplift of the crystalline basement in the southwest Sichuan, and heat flow decreases from the south, through the central area, to the northwest. This is caused by the structural forms and basement topography. The uplifted region of the crystalline basement has high heat-flow values, while depression areas produce low values. This suggests heat-flow refraction and re-distribution. Heat flow increases slowly from the Northwest Depression to the Central Uplift, and rises sharply from the East Depression to the Central Uplift. This distribution of heat flow is similar to earth temperature distribution. It suggests the gentle uplift of the crystalline basement from the Northwest Depression to the Central Uplift, and a more rapid rise from the East Depression to the Central Uplift, crossing the Mt. Huaying fracture zone. From the Central Uplift to the southwest, heat flow increases, particularly in the area between Longliusi and Weiyuan. This heat-flow gradient is coincident with the Longnusi-Weiyuan Palaeo-Uplift, and reflects a gradual increase of the uplift to the southwest.

Heat-flow values in the Sichuan Basin range from 52.7 to 103.0 mW/m^2 , with a mean value of 69.1 mW/m^2 . In the central, the northwest and the eastern areas, heat-flow

values range from 58.6 to 71.2 mW/m^2 , with a mean value of 66.1 mW/m^2 , while in the southwest and the south, it varies from 76.6 to 100.5 mW/m^2 , with a mean value of 86.2 mW/m^2 . Therefore, a high mean heat flow in the Sichuan Basin results from high mean values in the south and southwest of the basin. On one hand, the uplift of crystalline basement causes heat flow refraction and re-distribution. On another, from the results of magnetotelluric sounding, a highly conductive layer in the crust could raise the temperature in the south and southwest areas. Li (1987) believes that the high conductivity layer in the crust derives from partially molten granitic materials.

In fact, there is considerable tectonic activity in the southwest of Sichuan. The highly conductive layer in the crust probably gives rise to high heat flow in the region. To the outer edge of the southwestern portion, the Tibet platform is strongly uplifted due to the collision of the Indo-Chinese and Eurasia plates during the Himalayan epoch. This caused the Chuan-Dian rhombic plate to slip and shear to the southeast, and has left trace of early faulting activity on the edge of the southwest Sichuan, especially in the Xianshuihe-Anninghe-Zemohe fault zone, where there are many warm springs, and earthquake swarms are frequent. Under the compressive stresses from the southwest of the India Plate, the southeast of the Pacific Plate and the reaction from the block, northeast of Mt. Daba, the balance of force on the asthenosphere was lost causing mantle mass upwelling and the occurrence of a high conductivity layer within the crust at shallow depths (about 15 km). The high mean value of heat flow (86.2 mW/m^2) is close to the mean value for Cenozoic folded zones and active regions (87.1 mW/m^2). Another factor, which perhaps produces the high heat-flow values in the Sichuan Basin, is the thick crust (39-45 km). For example, the crustal heat flow in the northwest is 42.7 mW/m^2 (69% of the terrestrial heat flow), 37.7 mW/m^2 in the Central Uplift (53% of terrestrial heat flow), and 37.3 mW/m^2 in the south and southwest (43% of terrestrial heat flow).

4.3 Thermal Status of the Deep Crust

Heat flow on the surface derives from two sources: one is the crustal heat flow, which arises from the decay of radioactive elements in the crust, and the other is mantle heat flow from the bottom of the crust. For a typical structural unit, the crustal heat flow varies with enrichment of radioactive elements, and the thickness of the radioactive element-bearing layer. Mantle heat flow is constant in a stable region. In the different structural units, crustal heat flow can vary considerably. For example, the older geological regions usually have lowest values (about 41.3 mW/m^2 for the Archaean), but the Mesozoic to Cenozoic structural zones yield high heat flows (65.0 mW/m^2 and 72.1 mW/m^2), which is 1.5 times

greater than the stable areas (Jessop, 1990).

4.3.1. Calculation of Deep Heat Flow and Earth Temperature

The determination of crustal thickness and the distribution of radioactive elements in the crust is most important in obtaining deep heat flow and temperature values. The crustal model was determined by comprehensive analysis of deep seismic sections, aeromagnetic surveys, and exploration drill-holes. It is impossible to measure the abundance and distribution of the radioactive elements in the whole-crust in the study area directly. Wang et al. (1989) proposed a method for determination of radioactive element distribution, i.e. using step functions to simulate distribution, and assuming that the content of radioactive elements in a certain lithology section is a constant for different depths. They believed that this method is applicable for sedimentary basins. The radioactive content of rock samples from the Sichuan Basin was measured using ultra-heat neutron analysis. It was revealed that the radioactive content mainly depends on lithology, and depends little upon increase of depth. Therefore, the step function could be applied to radioactive element distribution in order to calculate deep heat flow and temperature.

For Sinian stratum and upper sections, heat generation due to radioactivity of rocks is given by:

$$A = 0.319\rho \times (0.73U + 0.2Th + 0.27K)$$

Here, A is the heat generation of radioactivity in HGU ($1\text{ HGU} = 0.41868\text{ }\mu\text{W}/\text{m}^3$), ρ is the rock density (Mg/m^3), U is the mass of ^{238}U , Th is the mass of ^{232}Th in ppm, and K is the percentage by mass of ^{40}K .

The radioactive heat generation for the Proterozoic strata and the lower crust was determined by considering the available values for the Heli Group (corresponding to the Ebian Group of the southwest crystalline basement in Sichuan). Because no samples were collected from the lower crust in the study area, the heat generation of radioactivity could only be calculated in the light of known data.

Deep crustal temperature was calculated using the expression for 1-D steady-state heat conduction (Buntebarth, 1984),

$$T_z = T_0 + \frac{qH}{\kappa} - \frac{AH^2}{2\kappa}$$

Here, T_z is the temperature at depth Z , T_0 is the surface temperature converted for each layer, q is the heat flow at the earth surface, H is the thickness of the strata, κ is the thermal conductivity, and A is the heat generation of the

rock.

4.3.2. Deep Heat Flow and Temperature

The mantle heat flow in the northwest, southwest and central areas are 23.0, 33.1 and 49.0 mW/m^2 respectively. The northwest and central Sichuan have low mantle heat flows, indicating a geologically stable region, whilst the southwest and south Sichuan have relatively high values, corresponding to the transition zone between the stable region and the Mesozoic to Cenozoic active region. The heat-flow data represent the tectonically and seismically activated areas of the southwest and south Sichuan, arising from the collision of the Indo-China and Eurasia plates during the Himalayan epoch, with strong uplifting of the Tibet Platform. This structural feature caused the Chuan-Dian rhombic plate to slip southward, and the Palaeo-Kangdi-Panxi Fault to reactivate. The compressive stress on the southwest of the collision zone caused mantle material to upwell, giving rise to high heat flow in the region. This can also be deduced from temperatures at the Moho Discontinuity. In the northwest, central and southwest of Sichuan, temperatures at the Moho are 606.4 $^{\circ}\text{C}$, 658.6 $^{\circ}\text{C}$ and 820.5 $^{\circ}\text{C}$ respectively. The northwest and central Sichuan have been measured at 660 $^{\circ}\text{C}$, which is similar to that in the stable east-American region. In the southwest and south Sichuan, the temperature at the Moho lies between 860 $^{\circ}\text{C}$ and 1115 $^{\circ}\text{C}$, which is consistent with the value for the ridge province of the Cenozoic active region, which lies in west American basin.

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