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DEEP HEAT FLOW AND GEOTHERMAL STRUCTURE IN SICHUAN BASIN OF CHINA

WANG Xuben[1], WANG Jiyang[2], LI Qingyang[1], YU Huijin[1]
[1]Chengdu University of Technology, Sichuan, Chengdu, 610059, People's Republic of China
[2]Institute of Geology, Academia Sinica, Beijing, 100011, People's Republic of China

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ABSTRACT

With a hybrid-crust heat-flow model, using the "peeling" method, we have investigated the deep geothermal structures of the southwestern and middle uplifts, and the northwestern depression and south lowly folded belt as well as eastern highly folded belt, Sichuan Basin of China. The temperature values at the Conard surface are in the range of 371-494 degree centigrade, and those at the Moho discontinuity are in the range of 552 - 821 degrees centigrade. Preliminary analysis of the bottom temperature of the sub-crust and the lithosphere temperature distribution indicates that Sichuan Basin is a stable tectonic unit relatively with fairly low temperature and heat flow except the southwestern part of the Basin.

1. INTRODUCTION

Birch et al. (1968), *Roy et al.* (1968), and *Lachenbruch* (1968) have described a two element linear relationship between surface heat flow, q_o, and heat production of shallow rocks, A_o, in plutonic areas:

$$q_0 = q_r + A_0 D \qquad (1)$$

where q_r is called the reduced heat flow (often considered as the upper-mantle heat flow) and A_oD represents the contribution from radiogenic source in the upper crust, with D being related to the characteristic thickness of the heat-generating layer. This relation means that the surface heat flow consists of two components, radiogenic-source heat flow and upper-mantle heat flow. It has provided a very useful and simple tool both for constructing heat generation models of the upper crust and for extrapolating surface data to the depths needed for analysis of deep geothermal structure. *Pollack* and *Chapman* (1977) indicated that this relation would be applicable in many non-plutonic settings. They also proposed a new empirical relation between reduced heat flow, q_r, and the mean heat flow of a province, q_o, such that $q_r \approx 0.6q_o$, to estimate the reduced heat flow in cases where heat-flow and heat-production data are not available. Combining linear relationship between mean heat flow and reduced heat flow with characteristic depths from a world-wide distribution of tectonic provinces, the results show that characteristic depth D lies within a quite restricted range: 8.5 ± 1.5 km.

Lachenbruch (1970) considered the distribution model of an exponential decrease of heat production with depth as the only possible explanation of the linear relationship of equation (2) given through differential erosion, although he explained three assumption models (step model, linear model and exponential model). *Swanberg* (1972) provided a field study to support the exponential source model by determining the nature of variation of heat production with depth in the Idaho Batholith.

Wang Jiyang et al. (1988), *Wang Jian, Wang Jiyang et al.* (1992) indicated that the exponential distribution model of radiogenic production is not applicable within sedimentary stratigraphic sequences. They further indicated that there are no uniform models to explain the distribution of heat production, because the distribution of radioactive elements in sedimentary strata depend mainly on lithological features related to sedimentary processes, depositional environments and other factors, according to their studies of deep geothermal structure in the Liao He and Hua Bei Basins of China.

2. CALCULATION OF DEEP HEAT FLOW

By measurements of neutron activation analysis and the chemical analysis of trace elements of rock specimens, we have determined the contents of radioactive elements U, Th, and K in sedimentary strata of Sichuan Basin (see Table 1), and calculated the radiogenic heat production in terms of the formula provided by *Birch (1954)* as follows:

$$A_0 = 0.1327\rho(0.73c_U + 0.20c_{Th} + 0.27c_K) \qquad (2)$$

where ρ is the mean density of a stratum, and c_U, c_{Th} and c_K represent the contents of U, Th, and K, respectively.

The results show that the distribution of heat production does not seem consistent with exponential decrease with depth (see table 1). To satisfy practical needs, we have designed a hybrid distribution model of radiogenic heat production in the upper crust of Sichuan Basin. For the case of one- dimensional steady-state heat flow, we assume that the second part of equation (1) comprises two kinds of calculating models, we simply define the second part of equation (1) as crust heat flow, q_C, $q_C = q_{C1} + q_{C2}$. For sedimentary sources, we utilize step models according to the following formula to calculate the heat flow, q_{C1}, contributed by sedimentary strata lying above crystalline basement at depth z_t:

$$q_{C1} = \int_0^{z_t} A(z)dz = \sum_{i=1}^{n} A_i z_i \qquad (3)$$

where n is the number of sedimentary layers, and A_i and z_i, two parameters, which can be determined, represent the mean heat production of each stratum and its corresponding thickness, respectively.

For plutonic sources of the basement, the model of exponential decrease in radiogenic heat production with depth is used to estimate the heat flow q_{C2} generated by materials lying between depths z_t and z^*. We assume that the heat flow $q(z^*)$ across the depth z^* is uniform throughout the province. The calculating formula is written as

$$q_{C2} = \int_{z_t}^{z^*} A(z_t) e^{-\frac{z}{D}} dz \qquad (4)$$

Where $A(z_t)$ represents the radiogenic heat production of materials at depth z_t and D is the thickness of the heat-producing enriched zone. We have calculated the D of different areas of the basin.

We have used this hybrid-crust heat-flow model to calculate the deep heat flows of several subtectonic units in the Basin. Figure 1 is one of the geothermal models in different sub-tectonics of the Basin, which illustrates the hybrid models of crust radiogenic heat-source distribution. For the upper part of this distribution, A_0 is the calculated value for each sedimentary layer above the stratum Pt; for the lower part, the exponential model is used.

3. CRUST GEOTHERMAL STRUCTURE

With the help of the crust heat distribution model, the deep geothermal structures have been estimated. The vertical temperature recursion formula can be written from resolution of the one-dimensional heat conducting equation:

$$T_i^{bottom} = T_i^{top} + q_i^{top} \frac{z_i}{k_i} - \frac{A_i z_i^2}{2k_i} \qquad (5)$$

This formula denotes that one can resolve the bottom temperature T_i^{bottom} of stratum i if one knows the top surface temperature T_i^{top} and top surface heat flow q_i^{top}, as well as the thickness z_i, thermal conductivity k_i, and radiogenic heat production A_i of the same stratum. The geothermal state at different depths can be estimated by using the so-called "peeling" method, extrapolating downward from the surface temperature according to the formula.

Further, lithospheric temperature features below the Moho discontinuity have been crudely estimated by using the above models and data. Taking the general rock thermal conductivity value of upper mantle as 3.4W/m°K, the mantle's geothermal gradient may be estimated by means of mantle heat flow. The assessed temperature-depth relations of different substructure units are shown in Figure 2. We can assess the depth of the asthenosphere from the intersection of the geothermal curve with the rock solidus. The rock solidus shown in Figure 2 comes from *Lachenbruch and Sass's* (1978) dry basalt solidus formula:

$$T = 1050 + 3z \qquad (6)$$

Where z represents depth in kilometers, and T is temperature at that depth in degree centigrade. With the estimation, we know that Weiyuan-Longnuchi uplift has a highest temperature at Moho discontinuity: 821.3 degree centigrade while the Tongjiang-Xintong Depression and East highly folded belt have lower temperature at the discontinuity. The value of Nanchong slope, Chengdu depression, and south lowly folded belt are located at a middle level. Chengdu depression, Tongjiang-Xintong depression, and East highly folded belt have the thickest lithosphere about 127 km. Weiyuan-Longnuchi uplift has the most thin lithosphere thick: about 75.6km. Nanchong slope and South lowly folded belt have lithosphere of the about 100km.

4. CONCLUSION

By means of calculating or estimating terrestrial heat flow and measurement of the uranium, thorium, and potassium contents of rock samples, we use a hybrid heat generation model to estimate the crust heat structure for the combination of plutonic basement overlain by sedimentary strata that is present in the basin. Then using this model, we have calculated the mantle heat flow of several subtectonic units in the basin. The surface heat-flow values range from 35 to 80 mW/m^2, with a mean value of 62.44mW/m^2, while the mantle heat-flow ranges from 22. mW/m^2 to 38.95 mW/m^2.

Using the "peeling" method, we have investigated the deep geothermal structures of the southwestern and middle uplifts, and the northwestern depression and south lowly folded belt as well as eastern highly folded belt. The temperature values at the Conard surface are in the range of 371-494 degree centigrade and those at the Moho discontinuity are in the range of 552 - 821 degrees centigrade (see table 2). Preliminary analysis of the bottom temperature of the sub-crust and the lithosphere temperature distribution indicates that Sichuan Basin is a stable tectonic unit relatively with fairly low temperature and heat flow except the southwestern part of the Basin

Table 2 has showed that the characters of deep heat flow and temperature structure in different sub-tectonic units of Sichuan Basin, the southwestern of China.

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TABLE 1 Stratigraphic contents of ^{238}U, ^{232}Th, and ^{40}K, as well as heat production, A_0, in Sichuan Basin

Stratigraphic unit	Major lithologicss	^{238}U (PPM)	^{232}Th (PPM)	^{40}K (%)	ρ(g/cm^3)	A_0 (μW/m^3)	Numbs. samples
Jurassic (J)	Sandstone, mudstone	2.9	12.8	2.37	2.54	4.06	2
Group Xujiahe of Triassic (Th)	Sandstone, mudstone, shale	2.9	9.7	2.73	2.54	3.86	4
Group Recoubuo of Triassic (Tr)	Limestone, dolomite, shale	2.9	0.08	0.16	2.68	1.80	1
Group Jialingjing of Triassic (Tc)	Limestone, dolomite	2.6	2.9	1.21	2.68	2.38	67
Group Feixianguan of Triassic (Tf)	Limestone, mudstone	0.61	.74	0.24	2.68	0.56	1
Permian (P)	Limestone, shale	0.84	2.91	0.37	2.70	1.11	57
Carboniferous (C)	Limestone, shale	3.4	1.00	0.24	2.70	2.35	5
Silurian (S)	Limestone, mudstone	2.7	15	3.29	2.74	5.09	2
Ordovician (O)	Limestone, shale, dolomite	.71	5.12	0.39	2.48	1.30	2
Cambrian(∈)	Limestone, dolomite	.85	2.55	0.92	2.82	1.22	4
Sinian (Z)	Dolomite	1.44	0.28	0.26	2.80	1.05	6
Upper-crust	Gneiss, migmatite,					4.20	45
Lower-crust						1.16	30

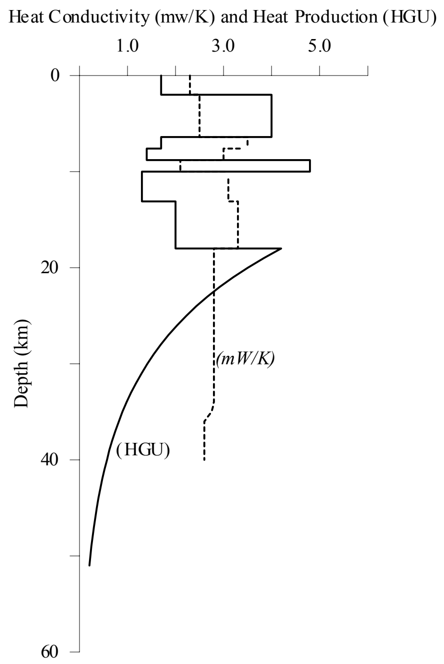

Figure 1 One example of crustal geothermal structure model in Sichuan Basin of China

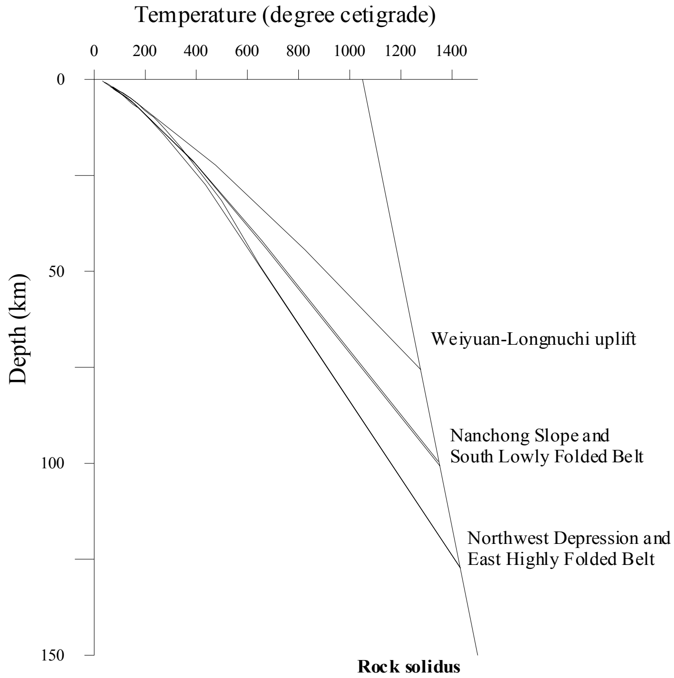

Figure 2 Deep geothermal structure in Sichuan Basin of China

Table2 Calculating results of deep heat flow and crust geothermal structure in Sichuan Basin

Structure units / Heat flow Or temperature	Chengdu depression	Tongjiang-Xintong depression	Weiyuan uplift	Nanchong slope	South lowly folded belt	East highly folded belt
q_0	59.24	58.94	67.83	60.80	60.71	55.82
Bottom of sediments	45.48	47.49	63.49	53.79	54.02	49.72
Bottom of metamorphic rock	41.82	44.14			50.77	44.60
Conard surface	27.97	31.28	46.38	39.65	39.59	33.62
Moho discontinuity q_r	21.92	25.59	38.55	32.21	31.77	27.64
q_r/q_0 (%)	37.0	43.1	56.84	53	52.3	49.5
D	10.81	10.1	13.45	11.11	8.78	8.63
Temperature at Corad surface	494.37	432.93	472.90	391.41	374.48	370.95
Temperature at Moho discontinuity	643.8	593.3	821.3	668.4	639.7	552.8
Thickness of lithosphere	127.0	127.3	75.6	99.5	100.7	126.8