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Causes of Geothermal Fields and Characteristics of Ground Temperature Fields

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ABSTRACT

There are many arguments on energy sources and main controlling factors of geothermal fields, so a systematic study on the distribution of ground temperature fields shall be necessary. In this paper, the cooling rate of abnormal heat source and the heat transfer of paleo-uplift model are simulated by using the forward heat conduction method of geothermal field. Combining with a large number of geothermal field exploration examples, the following conclusions are drawn: 1) The magmatic activity has no direct contribution to the modern geothermal field when the time of magmatic activity is more than 0.5Ma, and Tengchong and Qinghai-Tibet regions, which are most likely to have modern magmatic activities in the mainland of China, had their magmatic activities 0.5Ma years ago; 2) The temperature of most geothermal fields can be obviously divided into three sections from shallow to deep: high geothermal gradient (H), low geothermal gradient (L), and low temperature (D). Temperature contours on the profiles are mirror reflections, indicating that heat transfer is dominated by heat conduction, rather than by "heat sources" with abnormal high temperatures, which provide heat for geothermal fields. 3) Physical property difference (thermal conductivity) of near-surface (0-10km) strata is the main controlling factor of geothermal field.

1. INTRODUCTION

After all, there are a few geothermal fields related to magmatic activity, such as Iceland and Japan. In China and most parts of the world, only medium and low temperature geothermal fields can be found. In such an area, how to find economic, high ground temperature anomaly is the key of this paper.

Many scholars have done a lot of research on the causes of abnormal high ground temperature in geothermal fields (Chapman D. S., 1985; Lee W H K, 1970; Cermark V, 1989). It is generally believed that thermal convection in fault zones (Roy et al., 1972; villas and Norton, 1977; Turcotte and Schubert, 1982; Best and Christiansen, 2001); thickness of the mantle (Han Xiang-jun, 2002); radiogenic heat production (Qiu Nan-sheng , 2002); mantle magmatic activities (Berktold,1983; oskooi et al, 2005; Luis Urzua, 2002; Bai Jia-qi,2006), basement undulation (Ma Gang, 1983; Yan Dunshi,2000; Chen Mo-xiang, 1988; Gong Yuling, 2003) are the main factors of geothermal anomaly.

These influencing factors can be summed up in four aspects: heat source, heat transfer channel, thermal caprock and thermal reservoir. Except for the heat source, the other factors have been basically unanimously recognized (Mao Xiaoping 2018).

This paper has the following innovative points of view：

1)We propose first time that the temperature of geothermal field in China is divided into three sections in vertical direction, and have successfully explained the slow increase of geothermal gradient in the deeper strata of geothermal field.

2) We have divided the geothermal field into two categories first time: magmatic activity area (magmatic activity time < 0.5Ma), weak-magmatic activity area / non-magmatic activity area (magmatic activity time > 0.5Ma). The former can directly heat the geothermal field, while the latter can only be used as a heat transfer channel after magmatic activity.

3) The heat in the deep is supplied to the geothermal field by conduction rather than convection, and the distribution of the temperature field is determined by the physical properties in the shallow part of the earth's crust rather than by faults.

These three provide an important exploration model for finding geothermal fields in many areas with medium and low temperature background in China and the world.

2. GEOTHERMAL FIELDS AND MAGMATIC ACTIVITIES

The heat source of geothermal field is the key problem of the formation mechanism of geothermal field, because it determines the exploration method of geothermal field. As for the heat source, the first thing to think about is magmatic activity, which is a necessary condition for the formation of high temperature geothermal fields. In geothermal well drilling, if we can drill directly and close to the magma chamber, there will be an endless stream of heat, which is extremely beneficial to geothermal development. Several famous geothermal fields are related to recent magmatic activities in the vicinity. For example, the Geysers geothermal field developed since 1960 in the United States has a modern volcano Tyler Valley 5 km north of it (Schmitt, 2003).

Similar hot geothermal fields in China hope to be found, but failed. It is found that although there is magmatic activity in China, the magmatic activity is earlier than that of 0.5Ma. Wang Shubing (2015) believes that Yunnan Tengchong stopped magmatic activity 0.5Ma ago. Wu Zhenhan (2005) believed that magmatic intrusion ended at 11Ma in Qinghai-Tibet region. In eastern China, there are also a large number of magmatic activities, but they all occurred in the pre-Mesozoic era. As time goes on, magma intrudes into the shallow strata and cools faster when it ends the intrusion. Numerical simulation of heat conduction shows that the heat of

magmatic activity has not contributed directly to the geothermal field when the depth of the intrusion of the magmatism is less than 10km and the invasion time is more than 0.5Ma. Duan Wentao (2017) simulated the cooling time of magma with diameter 1km invading the depth of 10km. The conclusion is that it takes only 0.2Ma to cool to 95% of the initial temperature. Therefore, in the process of heat conduction from the interior of the earth to the surface, the dynamic equilibrium process of temperature is quickly completed, which is much longer than the time of geological action. Compared with the time scale of millions of years, this process is almost completed in a moment.

3. GEOTHERMAL FIELDS AND MAGMATIC ACTIVITIES

There is no high temperature geothermal field related to magma in eastern China, but scholars still hope to find a "heat source" for some medium and low temperature geothermal fields; even if there is no heat source, they still hope to find a large fault in order to communicate the deep heat source. From the point of view of the medium-low temperature geothermal field discovered at present, there is a peculiar phenomenon that temperature varies with depth: the temperature gradient under the geothermal field decreases sharply with depth. Ground temperature can be divided into 2-3 segments from shallow to deep: high gradient section H, low gradient section L and low temperature section D. This means that heat in the deep is transferred by conduction.

Taking Yangyi Geothermal Field in Tibet as an Example, Figure 5 is the temperature variation curve of ZK212 deep well in Yangyi geothermal field, Qinghai-Tibet Plateau(Liu Haiyang, 2014). It can be seen that the temperature can be divided into two sections from shallow to deep: the high geothermal gradient section H and the low geothermal gradient section L, with a depth of 380m as the boundary, and the upper section(H) has Quaternary caprock, which can reduce the heat loss. The bottom temperature of the H section soon reaches the highest temperature 105 ºC. The thickness of section L is about 1000m, but its geothermal gradient is small, only 24 ºC/km.

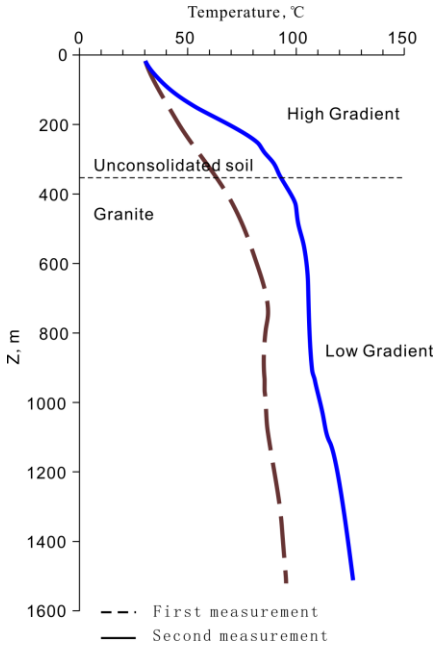


Figure 1: Temperature curve of well ZK212 of Yangyi Geothermal Field on Qinghai-Tibet(Liu Haiyang, 2014).

This phenomenon is universal. The following figure shows the geothermal distribution curves of some wells in Sirte, France (Baria et al, 1994). These curves can also be divided into several sections, 0-1200m is section H, 1200-3500m is section L, the thickness is nearly 2300m, the geothermal gradient is very low, and the temperature increases slowly.

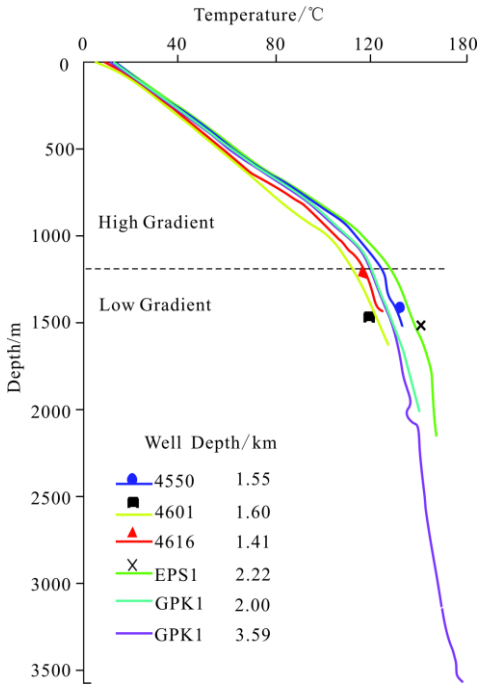


Figure 2: Geothermal Distribution in Surz, France

Figure 3 shows the temperature curve of Xinzhou geothermal field in Yangjiang City, Guangdong Province (Lin Wenjing, 2016). In the depth range of 80-160m, the temperature reaches 75-80ºC(H section) rapidly, and then increases slowly (L section) in the depth range of 160-1100m, then increases to 95 ºC at 700m and 106 ºC at 1000m.

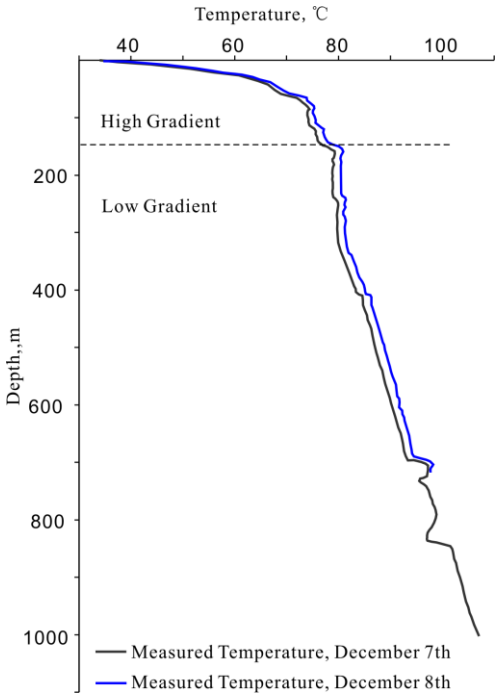


Figure 3: Temperature Curve of Xinzhou Geothermal Field in Yangjiang City, Guangdong Province

In the GRY1 well in Xianxian County, Hebei Province, high temperature anomaly does occur at the depth of 1000m (H section), while the temperature increases slowly in the depth range of 1000 - 3700m (L section). Compared with well Ninggu 4 in Raoyang Basin, which is located in the northwest of the well (Wei Wei, 2016), the temperature of the two wells is equal at the depth of 3700 m (106 ºC), but below 3700 m, the temperature of GRY1 is lower than that of well Ninggu 4 (section D). In other words the temperature of the well is divided into three sectiones. The other three curves in the figure 4 are the temperature curves of CCSD-1 well, Anfeng Town, Donghai County, Jiangsu Province; well SN5 in Shuntuogule low uplift area, Tarim Basin; Long651 well in East Chengdu. They represent the temperature distribution of most normal geothermal areas (basin area, rock or rock mass exposed area) in China: the temperature shows a linear increasing trend.

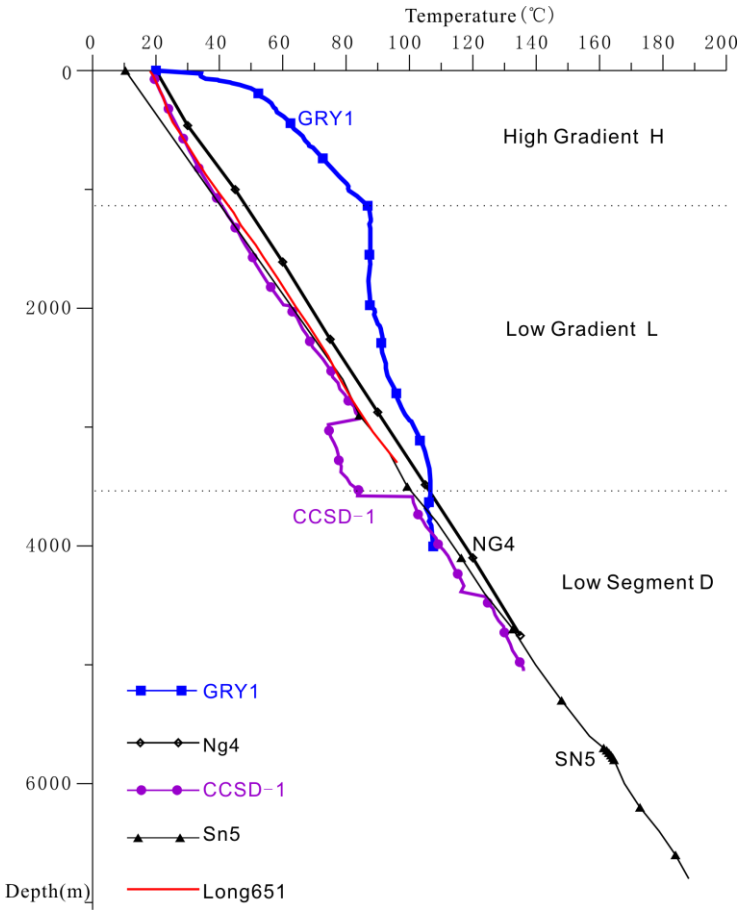


Figure 4: Comparison of temperature measurement curves between GRY1 well Xian County, Hebei Province and Ninggu 4 well Raoyang

What causes the geothermal gradient in the deep part of the geothermal field to decrease sharply and be divided into three sections? Many scholars believe that the decrease of temperature gradient in geothermal field is not an inevitable phenomenon. It is the groundwater on the side that cools the geothermal field and disturbs the ground temperature by convection. Without this disturbance, the geothermal temperature may be higher (Yao Zujin, 1986).

4. THEORETICAL SIMULATION OF GEOTHERMAL FIELD TEMPERATURE DISTRIBUTION

In order to explain the above phenomena, we design an ideal model to calculate the temperature field distribution caused by the difference of formation thermal conductivity under the normal background of basement heat flow.

A theoretical model of paleo uplift is shown in Figure 5. The black thick line is the shape of paleo-uplift. This model can represent most cases in which the high thermal conductivity layer developed in the shallow part of the paleo-uplift or intrusion of rock mass. The paleo-uplift at the bottom of the model is 1 km in width and 2 km in height, and its thermal conductivity is taken as the average thermal conductivity of Paleozoic strata k3=3.0 W/(m· ºC); the top of the model is covered with a 200 m thickness thermal resistive layer whose thermal conductivity is taken as the average thermal conductivity of Quaternary system k1=0.6 W/(m· ºC); the surrounding rock K2 is set up with different numerical values for numerical simulation. The mantle heat flow Q is set to mean 71.8 mW/m^2 in the continental region. After the simulation time reaches 0.1Ma, the temperature field basically enters the steady state.

From the following simulation results, it can be seen that the temperature isoline is mirror symmetrical if the horizontal line passing through the M point of the center of the paleo-uplift is taken as the axis. In the paleo-uplift area, the temperature from shallow to deep can be divided into three sections H, L and D. Among them, the top of the uplift (above point B) is the high geothermal gradient section H; the section from point B to M belongs to the low gradient section L; and the area below M is the low temperature section D compared with other areas with the same depth, that is, the temperature of the uplift area is lower than other normal temperature areas. Therefore, it can be explained that the temperature of GRY1 well in Xianxian uplift zone is lower than that in normal geothermal area under 3700 m (Ninggu 4 well in basin area).

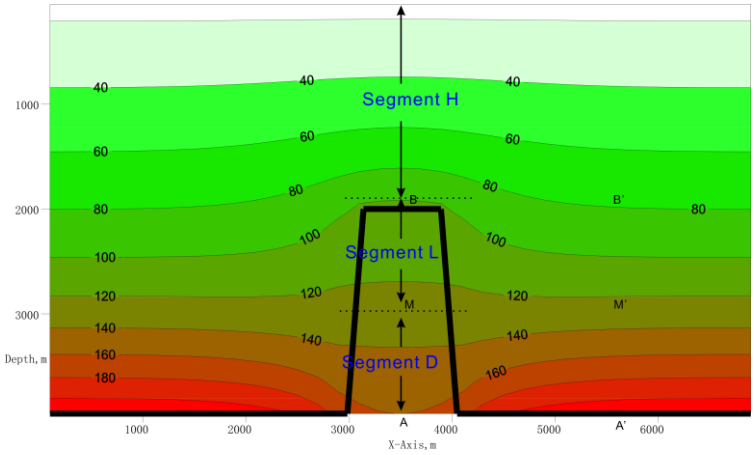


Figure 5: Temperature profile in paleo-uplift area

As long as there are high heat conduction layers such as paleo-uplift and magmatic rock mass near the surface, and the Quaternary caprock with a certain thickness is covered above them, the moderate-low temperature geothermal field of the present scale can be formed only by the difference of thermal conductivity of the stratum, which has nothing to do with magma chamber, radioactivity, fracture penetration, etc. It can be concluded that the medium-low temperature geothermal field or geothermal field mainly depends on the physical property difference within the range of 0-5 km near the surface, and the heat transfer mode is mainly heat conduction.

5. EXAMPLES OF THE DISTRIBUTION OF BASIN GEOTHERMAL FIELD

The uplift zone in the middle of the model shown in Figure 5 above can be regarded as the uplift zone of the basin margin or the interior of the basin, and the two sides can be regarded as the normal basin sedimentary area in the interior of the basin. It can be seen that the temperature at the top of the uplift is higher than that in the basin area at the same depth; if the depth increases to the basement of the basin, the temperature in the uplift area is lower, while the basement temperature in the basin is higher. If the basement of the basin margin is exposed, the necessary conditions for the formation of high geothermal temperature (Quaternary caprock) are lost, then there will be no high geothermal anomaly in the shallow part of the uplift zone, so the phenomenon of high heat flow in the basin area is more significant.

The average geothermal gradient in Sichuan Basin is only 22 °C /km while in the northern part it is lower than 15 °C /km, which is lower than the average 30 °C /km in the continental area (Han Yonghui, 1993). This is because there is no caprock in the basin, and the Jurassic and Triassic strata are exposed on the surface.

Jiyang Depression and Songliao Basin have thick Quaternary caprock and Tertiary sedimentary layer, which can prevent heat loss, so they have high heat flow. Unfortunately, the classical geological theory, the formation of rift basins, interprets this phenomenon as a result of lithospheric stretching and thinning and mantle upwelling, i.e. high heat flow caused by direct heating of the basement of the basin by deep mantle heat. This obviously needs to be questioned.

5. CONCLUSION AND DISCUSSION

The following conclusions can be drawn:

1) There is no recent magmatic activity in the continental area of China (less than 0.5Ma years).

2) Vertical distribution of temperature in medium-low temperature geothermal field can be divided into three sections, which shows that heat transfer mode is mainly heat conduction, while faults and radioactivity have little influence on geothermal field.

3) The time of tectonic evolution is much longer than that of geothermal dynamic equilibrium. The distribution of temperature field is determined by the difference of physical properties in shallow crust.

4) Some classical geological theories dependent on temperature may be wrong, such as the interpretation of the high heat flow of the basement in the formation mechanism of the rifting basin.

REFERENCES

Chapman D. S. and Rybach L.: Heat flow anomalies and their interpretations[J]. J. Geodynamics, 4, (1985), 3-37.

Lee W H K.: On the global variations or terrestrial heat flow[J]. Phys. Earth Planet. Inter, 2, (1970), 332-359.

Cermark V, Rybach L: Vertical distribution of heat production in the continental Crust[J]. Tectonophysic, 159, (1989), 217-230.

Roy R F, Klackwell D D and Decker E R. 1972. Continental heat flow. In: Robertson EC(ed). The Nature of the Solid Earth. New York: McGraw-Hill: 506-543.

Villas R N and Norton D L: Irreversible mass transfer between circulating hydrothermal fluids and the Mayflower Stock. Econ. Geol., 72(8), (1977), 1471-1540.

Turcotte D L and Schubert G.: Geodynamics: Application of Continuum Physics to Geological Problems. New York: John Wiley and Sons. Inc., (1982).

Best M G and Christiansen E H.: Igneous Petrology. Blackwell Science Ltd., (2001), 1-458.

Han Xiang-jun, Jin Xu: Geothermal Resource And Thermail Structure In North- eastern China, Geology and Prospecting, 38(1), (2002), 74-76.

Qiu Nan-sheng: Characters Of Thermal Conductivity And Radiogenic Heat Production Rate In Basins Of Northwest China, Chinese Journal of Geology, 37(2), (2002), 196-206.

Berktold A. Electromagnetic studies in geothermal regions. Geophysical Surveys, 6(1-2), (1983), 173-200.

Oskooi B, Pedersen L B, Smirnov M, et al.: The deep geothermal structure of the Mid-Atlantic Ridge deduced from MT data in SW Iceland, Phys. Earth Planet. Inter., 150(1-3), (2005), 183-195.

Urzua Luis, Powell T, Cumming W B, et al.: Apacheta, a New Geothermal Prospect in Northern Chile. Geothermal Resources Council Annual Meeting, (2002).

Bai Jia-qi, Mai Lin, Yang Mei-ling: Geothermal Resources And Crustal Thermal Structure Of The Qinghai-Tibet Plateau, Journal of Geomechanics, 12(3), (2006), 354-362.

Ma Gang, Chang Enxiang, Zhou Ruiliang, et al.: A Preliminary Investigation on the Characteristics of a Geothermal Field and the Conditions for its Formation in the Northern Part of the North China Plain, Bulletin of the 562 Compremensive Geological Brigade Chinese Academy of Geological Sciences, 4, (1983), 109-126.

Yan Dunshi, Yu Yingtai: Evaluation and utilization of geothermal resources in oil and gas area of Beijing-Tianjin-Hebei, Wuhan: China University of Geosciences Press., (2000).

Chen Mo-xiang, Deng Xiao: The Map of Geothermal Gradient of Cenozoic Sedimentary Cover in The North China Plain and its Brief Explanation, Scientia Geologica Sinica, 3, (1990), 270-277.

Gong Yuling, Wang Liangshu, Liu Shao-wen, et al. Distribution characteristics of terrestrial heat flow in Jiyang Depression, Science in China(D), 33(4), (2003), 384-391.

Mao Xiaoping: Genetic Mechanism and Distribution Characteristics of High Temperature Anomaly in Geothermal Field. Acta Geoscientica Sinica., 39(2), (2018), 216-224.

Mao Xiaoping,Wang Xinwei, LiKewen, Guo Shaobin: Sources of Heat and Control Factors in Geothermal Field. Earth Science, 43(11), (2018), 4256-4268.

Axel K. Schmitt, Marty Grove, T. Mark Harrison, Oscar Lovera et al.: The Geysers-Cobb Mountain Magma System, California (Part 2): Timescales of pluton emplacement and implications for its thermal history. Geochimica et Cosmochimica Acta, 67(18), (2003), 3443–3458.

Wang S B, Fu J L, Li C Z, Jiang F C, Tian G Q: Preliminary Division for Neotectonic Episode of Tengchong Block, South-west Yunnan. Geological Bulletin of China, 34(1), (2015), 146-154.

Wu Zhenhan, JIANG Wan, Zhou Jirong, et al.: Thermal-Chronological Dating on the Thermal History of Plutons and Tectonic-Landform Evolution of the Central Tibetan Plateau[J]. ACTA Geologica Sinica, 74(4), (2001), 468-476(in Chinese with English abstract).

DuanWT, HuangSP, Tang X Y and Zhang J: Numerical simulation of the thermal diffusion of volcanic magmatism with ANSYS WORKBENCH[J]. Acta Petrologica Sinica, 33(1), (2017), 267-278(in Chinese with English abstract).

Liu Haiyang: Temperature and Pressure Analysis of ZK212 in middle-deep Well of Yangyi Geothermal Field. Master's thesis of China University of Geosciences (Beijing), 24, (2014).

Baria R, Baumgärtner J, Gérard A. Status of the European hot dry rock geothermal programmer[J]. Geothermal Engineering, 19(1/2), (1994), 33-48.

Lin Wenjing, GAN Haonan, WANG Guiling, MA Feng: Occurrence Prospect of HDR and Target Site Selection Study in Southeastern of China. ACTA GEOLOGICA SINICA, 90(8), (2016), 2043~2058.

Wei Wei, Jiang Youlu,Yang Dexiang,et al.: Coupling relationship between diagenetic evolution of sandstone reservoirs and hydrocarbon accumulation in Palaeogene in Hejian trough, Raoyang Depression, Bohai Bay Basin, China[J]. Natural Gas Geoscience, 27(8), (2016), 1477-1488.

Yao Zujin: An Assessment of Geothermal Resources In Yangbajing, XiZang(Tibet). In: Chinese Academy of Geological Sciences. Journal of Institute of hydrogeology and engineering geology (2). Beijing: Geological Publishing House,12, (1986).

Han Yonghui, Wu Chunsheng. Geothermal gradient and heat flow values of some deep wells in Sichuan basin. Oil & Gas Geology, 14(1), (1993), 80-84.