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STUDY ON KUNMING LOW-TEMPERATURE GEOTHERMAL FIELD

Xu Shiguang and Xin Yong Yunnan Geological Engineering Survey Institute, 650041 Donjiawan, Kunming, P.R. CHINA

Key Words: low-temperature geothermal field, reservoir, faults, conceptual model, stored heat

ABSTRACT

Situated a few hundred kilometers eastwards to the so-called 'Himalayan Geothermal Zone' in SW-China, Kunming low-temperature fracture dominated geothermal field has been explored and exploited for spa, feeding fish, growing flowers and drinking as mineral water since 1970s. Nearly one hundred productive wells were drilled one after another during previous years, and a large quantity of hot groundwater was extracted from the reservoir each year. Somehow, a systematic study on the field was lacking. It is essential to establish the conceptual model and furthermore to evaluate geothermal reserve of the reservoir. This study shows that, with a lower conductivity, the unconsolidated overburden in Kunming basin enclose the enormous heat flow that conducts from the deep crust along several huge faults in the base. As a result, the groundwater in the reservoir has been heated up to form a semi-closed and layer-buried low-temperature geothermal field, whose origin comes from rain. Both the area and the stored heat of the field are comparably larger, and the field has been cut into six blocks by the faults. Each block has different characteristics. Further research needs to be conducted to develop a managerial model so as to avoid any potential environmental impacts and utilize the geothermal resource in the best way.

1. INTRODUCTION

Kunming, the capital city of Yunnan province in SW-China, is one of the most famous cities for tourism due to its beautiful scenery, warm climate and numerous scenic spots and historical sites. Geographically, Kunming is a faulted intermontane basin surrounded by hills and medium high mountains. The area of the basin, including of the Dianchi lake area, is about 600 km^2. The first well that revealed hot groundwater existence in Kunming basin was drilled at a depth of 659.39 meters in 1975, which led to a geothermal exploration during 1980s. It has been proven through the exploration that both the area and the stored heat, together with the hot water reserve are huge, and the roof of the reservoir is buried at 400 to 1500 meters depth. Furthermore, the steady pumping flow rates from a single well is comparably large. Needless to say, the reservoir is so suitable for drilling productive wells that an extensive exploitation has been undertaken. So far, nearly one hundred productive wells have been drilled. Another reason for the interest in the exploitation is that they contain several trace elements such as Li, Sr, I, Br, Cu, Mn, Mo, Fe, Zn, Ba etc., which are good for health, in the hot groundwater. Therefore, the hot groundwater has been utilized as mineral water for drinking after its qualification assessment. In addition to the appropriate temperature, hot groundwater also contains some appropriate substances such as Rn, Ra, H_2SiO_3, SO_4^{2-}, which has curative effect for such disease as dermatosis, rheumatism, and enterocolitis while being used in the spa. Thus, most of the hotels and sanatoriums drilled their own productive wells as early as possible so as to attract more customers as a supplementary service facility. Being used to feed fishes and to grow flowers besides mineral water and spa, the hot groundwater has been playing an important role in improving Yunnan's economic growth and in attracting foreign capital.

2. GEOLOGICAL BACKGROUND

2.1 Strata

Almost all of the formations within Kunming Geothermal field belong to sedimentary origin. According to borehole core records, quite a few strata, including of Mesozoic Erathem, Lower Series of Devonian System, Silurian System, Ordovician System and upper Series of Cambrian System, are missing. Any others are briefly summarized in table 1.

Z_2dn is the geothermal reservoir in the field, all of its upper strata, especially the unconsolidated overburden (Q and N), constitute the caprock with the lower conductivity. Every carbonate rock formation constitutes a good cold water aquifer, while each clastic rock formation constitute an aquitard. Some parameters of all the strata are shown in table 2.

2.2 Tectonics

Regionally, the Kunming basin is situated in the crossing of Diandong longitudinal tectonic zone and latitudinal tectonic zone, where the tectonic framework appears as 'cross' style. North-southern faults, which extend ten to hundred kilometers with displacement over 20 kilometers, constitute the controlling tectonics in the Kunming basin, and along which several magmatic intrusions and eruptions were found. East-western faults, on the other hand, are mostly confined and even displaced by the former, so they seem to be more or less discontinuous.

Puduhe fault, one of the North-southern faults, is an active one with a total surface extension of 300 km, dips to east, and displaces unconsolidated overburden of Quaternary System, along which there happened more than 5-intensity earthquake and formed many hot springs. It splits into six branches (F_7, F_8, F_9, F_{10}, F_{13} and F_{14}) while coming across Kunming basin. These branches, along with some confined east-western ones such as F_4, F_{12}, F_{41} etc., form and control Kunming geothermal field. The tectonic framework, together with the unconsolidated overburden thickness of the field are shown in Fig.1, while the features of the major faults in the field are summarized in table 3.

It is obvious to see from table 3 that most of the major faults in Kunming geothermal field belong to active reverse or reverse-slip faults with pressure-wrench property, which usually lead to a result that these faults are laterally impermeable and non-conductive, but may have vertical permeable and conductive.

3. GEOTHERMAL CONDITIONS AND CONCEPTUAL MODEL

3.1 Boundaries of the geothermal field

Compared with the rock layers, the conductivity of the unconsolidated overburden is much lower, which suggests that the boundaries of the field are mainly located within the basin plain where the unconsolidated overburden exist. Yet, in the mountainous region around, Z_2dn aquifer reserves are just cold water, for it lacks a good caprock.

Fault F_{25}, which is the eastern boundary of the lacustrine Kunming basin, behaves somewhat waterproof. The reservoir temperature in its east block is less than 40^0C, and is lower than the west block. Thus, it is considered as the eastern boundary of the field. Fault F_7, a pressure-wrench one with developed fracture zone, is laterally impermeable and heat isolated. For example, two boreholes just about 600 meters apart from each other were drilled near Baiyukou, and both of them penetrated Z_2dn aquifer that is horizontally connected through F_7, somehow the measured reservoir temperature in the west block is just 25^0C, while in the east block it is 17.5^0C higher. In addition, F_7 is the western boundary of the lacustrine Kunming basin. Therefore, it is considered as the western boundary of the field. Fault F_4 and F_{40} are displaced and confined by several big north-southern faults such as F_8, F_9, F_{10}, F_{13}, and F_{14}. The reservoir temperature in its north block is obviously lower than that is in its south block. For instance, a borehole with depth of 750 meters was drilled near Xiaoba in the north block and the measured reservoir temperature is just 26^0C, which is about 14^0C lower than that is in the south block. Similar results occurred near Hanjiacun. All of these phenomena indicate that F_4 and F_{40} are the northern boundary of the field. F_{31} and F_{32} are regarded as southern boundary of the field, for the boreholes located in their south block show about 28^0C reservoir temperature, which is obvious lower than that is in the north block.

On the whole, there exists significantly reservoir temperature difference between the two blocks of the big faults mentioned above. Therefore, it is reasonable to consider them as the boundary of the field.

3.2 Division of the geothermal blocks

Based on the faults in Kunming basin, the field can be roughly divided into six blocks (see Fig.1), whose reservoir temperature, groundwater quality type and water level are more or less different from each other. The basic data of these six blocks are given in table 4.

3.3 Features of the field

3.3.1 Temperature feature

The map of reservoir temperature at 700meters depth shows that a distinct high temperature center situated in the north of Jiujia along F_7 has been formed, and the reservoir temperature decreases gradually from this center to the edge of the basin. Vertically, within the field, the temperature in the caprock appears as a linear increase with the depth, and the geothermal gradient is about 5 to 6^0C/100m. However, this increase becomes comparably negligible in the reservoir when measured points enter a convective system (see Fig2 (a)). Outside of the field, although the temperature also increases with depth in the caprock, the geothermal gradient is significantly reduced by several to more than ten times, even if the point is just a few hundred meters away from the field boundaries defined above (see Fig.2 (b)).

3.3.2 Chemical feature

From the edge of the field to Jiujia high temperature center, the chemical composition of the hot groundwater becomes more complicated with the increase in reservoir temperature. The salinity and the content of some compositions such as SiO_2, SO_4^{2-}, Cl^-, K^+, Na^+ and Fe^{3-} etc. also have an increasing tendency, which lead the groundwater chemical type to have accordingly a similar change (see Table 5).

Generally, the salinity of the hot groundwater is between 0.13 and 0.72 g/L, and the pH value is from 6.8 to 8.2, which have no obvious difference with the values in the upper cold water aquifers. Possibly, this fact may indicate a close relationship of the hot groundwater with the upper cold groundwater, and that the reservoir is a semi-closed system. Anyway, this possibility has been proven by isotopic analysis: the testing result shows that, for D and ^{18}O, there is a certain difference between surface water and groundwater, but almost no difference between cold and hot groundwater, furthermore δD and δ^{18}O in different kinds of water appear close to international rain line, which illustrates that the origin for both cold and hot groundwater comes from the rain.

3.3.3 Pressure feature

Based up on the systematic measured water level data in the dry season in 1989, hot groundwater flows from the edge to the center of the field under a slightly productive condition. However, the hydraulic gradient is only 0.5‰ to 4‰, yet there is no instinct discharge approach. Therefore, an inference that the initial pressure distribution is somewhat flat and the reservoir is a better-closed one seems to be reasonable. Only artificial pumping will result in a significant pressure difference and drive hot groundwater flow towards the productive area.

Qualitatively, iso-pressure distribution map in 1989 reveals the hydraulic relationship between the adjacent geothermal blocks. Water level in block Ⅰ and block Ⅱ is uniformly distributed, which demonstrates the permeable nature of F_9 and F_{10}. However, a 2~17 water level difference between block Ⅱ and block Ⅲ, and a 4~8 water level difference between block Ⅲ and block Ⅳ reflect impermeable characteristics of F_{13} and F_{14}.

Data from observational wells show that the annual water level change in the reservoir is less than 4 meters, and it is not affected by the rainfall, but obviously controlled by production. Furthermore, it appears to decrease with time (see Fig.3).

3.4 Conceptual model

From the description and discussion above, a conceptual reservoir model of Kunming geothermal field can be established as shown in Fig.4. Recharging to the cold water aquifer, rainfall turns into groundwater, and some of which continue to flow down to the reservoir along some big north-southern faults such as F_7 and F_{25}. On the other hand, the reservoir is a semi-closed system without distinct discharge approach, so it has been heated up by absorbing the enormous heat flow that conducts from the deep crust along big north-southern faults in the base, especially along F_{13} .

4. GEOTHERMAL RESERVOIR ASSESSMENT

4.1 Stored heat

Since the reservoir is a layer-buried one, which has been cut into six blocks, the appropriate method － volumetric assessment is employed. The governing equation is as follow:

$$Q_R=CAh(t_r-t_j) \quad (1)$$

where Q_R──Stored heat in the reservoir (kJ)

A──Area of the reservoir (m^2)

h──Thickness of the reservoir (m)

t_r──Average reservoir temperature (^0C)

t_j──Reference temperature (^0C). Mean annual surface temperature in Kunming is used: $t_j=17^0C$

C──Average heat capacity of rock and water ($KJ/m^3 \cdot {}^0C$), determined by the following equation：

$$C=\rho_r C_r(1-\phi)+\rho_\omega C_\omega \phi \quad (2)$$

where ρ_r、ρ_ω──Density of rock and water (kg/m^3)

C_r、C_ω──Heat capacity of rock and water

ϕ──Porosity of rock (%). Calculated value from laboratory is employed: $\phi=3.5\%$

4.2 Stored water quantity

Stored water quantity consists of the water volume filling in the reservoir pores and the elastic expansion after discharge to the surface. The governing equation is as follow:

$$Qs=Ah\phi+SA(Z-H) \quad (3)$$

Where Qs──Stored water quantity(m^3)

S──According to pumping tests, $S=10^{-6}$

Z──Depth of reservoir roof(m)

H──Depth of water level(m)

Calculated results from (1) and (3) are summarized in table 6. Total stored heat is 126.6EJ, and total stored water quantity is $5.15Gm^3$.

5. CONCLUSIONS AND SUGGESTIONS

The main conclusions and suggestions of this study are:

(1). Kunming low-temperature geothermal field is a fracture dominated and layer-buried one, that is controlled by some big faults and can be roughly divided into six blocks. The geothermal gradient of the field is 4.5 to $6^0C/100m$.

(2). The field is located within Kunming basin due to significantly lower conductivity of unconsolidated overburden. F_{25}, F_7, F_4, F_{40}, F_{31} and F_{32} are the distinct boundary of the field. They are laterally impermeable and heat isolated, but may have vertical permeable and conductive.

(3). Z_2dn reservoir is buried at 400 to 1500 meters depth in Kunming basin, and its temperature is 40 to 73 ^0C. A distinct high temperature center situated in the north of Jiujia along F_7 has been formed, and the reservoir temperature decreases gradually from this center to the edge of the basin.

(4). The reservoir is a semi-closed system without distinct discharge approach. However, its pressure is not obviously affected by rainfall even though the origin comes from the rain.

(5). Fault F_9 and F_{10} are permeable, while F_{13} and F_{14} are laterally impermeable.

(6). Proven area of the field is $373.3km^2$. Total calculated stored heat is 126.6EJ, and total calculated stored water quantity is $5.15Gm^3$.

(7). Intense exploitation will inevitably result in a tremendous water level draw down. Therefore, further research needs to be conducted to develop a managerial model so as to avoid any potential environmental impacts and utilize the geothermal resource in the best way.

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TABLE 1: Stratigraphic column within Kunming geothermal field

Stratigraphic time			Code	Thickness in borehole (m)		Brief description of lithology
Erathem	System	Group name		Between	average	
Cenozoic	Quaternary		Q	0~350		Clay, with silt and sandy gravel interstratifications
	Tertiary		N	130~440		Sandy clay with lignite and sand interstratifications
Palaeozoic	Permian	Emeishang	$P_2\beta$	80~1356		Basalt with basalt ash tuff
		Qixia, maokou	P_1q+m	284~845		Limestone and dolostone
		Daoshitou	P_1d	1.8~99	21.8	Aluminous claystone and shale
	Carboniferous	Weining	C_2w	38.1~148	87.1	Limestone and bioclastic limestone
		Daitang	C_1d	71.1~164	94.3	Dolostone with shale and sandstone
	Devonian	Zaige	D_3zg	68.8~101	88.5	Dolostone with dolomitic limestone and lime-rubble rock
		Haikou	D_2h	8.6~44.3	34.0	Quartz sandstone with laminated siltstone and shale
	Cambrian	Shuanglongtan	$\in_2s$	54.9~100	77.5	Muddy dolostone with siltstone
		Doupuosi	$\in_2d$	1.2~101	53.1	Sandy claystone and micaceous siltstone
		Longwangmiao	$\in_1l$	32.3~164	92.1	Dolostone and muddy dolostone
		Canglangpu	$\in_1c$	86~258.5	198.2	Silty claystone, sandstone and quartz sandstone
		Qiongzhusi	$\in_1q$	106~338	246	Claystone, carbonaceous shale and phosphatic sandstone
Proterozoic	Sinian	Dengyin	Z_2dn	400~602		Dolostone and siliceous dolostone

TABLE 2: Some parameters of the strata in the field

Type		Stratigraphic Code	Unit flowrate (L/s·m)	Permeability (m/d)	Heat capacity (kJ/kg·⁰C)	Conductivity (W/m·⁰C)
Unconsolidated overburden		Q and N	0.31～1.75	0.04～1.85		0.983
Other caprock	Carbonate rock	P_1q, P_1m, C_1w, C_1d, D_3zg, $\in_1l$	1.19～5.37	0.418～113.2		3.50
	Clastic rock	D_2h, $\in_2d$, $\in_1c$, $\in_1q$	0.02～0.24	0.107～0.810		3.265
Reservoir		Z_2dn	0.092～2.7	0.087～2.98	0.92	5.10

TABLE 3: Features of the major faults in the field

No.	Strike	Length (km)	Dip direction	Dip angle	Classification	Mechanical property	Fault activity
F_4	East-west	14					
F_{12}	East-west	8.5	350^0	75^0	Reverse-slip fault	Pressure-wrench	Active
F_7	North-south	>65	East		Reverse fault	Pressure-wrench	Intense active
F_8	North-south	15					Active
F_9	North-south	25	West			Tension-wrench	Active
F_{10}	North-south	>23	East	37^0~35^0	Reverse-slip fault	Pressure-wrench	Active
F_{13}	North-south	42	East			Tension-wrench	Active
F_{14}	North-south	98	East	32^0~45^0	Reverse-slip fault	Pressure-wrench	Active
F_{20}	North-south	15	East	30^0	Reverse fault	Pressure-wrench	Active
F_{25}	North-south	>73	East	60^0~85^0	Reverse-slip fault	Pressure-wrench	Active
F_{31}	NE 65^0	21	South-east		Normal fault	Tension-wrench	
F_{32}	NE 75^0	20	South-east		Reverse fault	Pressure-wrench	

TABLE 4: Basic data of the geothermal blocks

NO.		Boundaries of the block	Area (km^2)	Geothermal gradient (^0C/100m)	Unconsolidated overburden thickness (m)	Strata code	Depth of reservoir roof (m)	Reservoir temperature (^0C)
Block Ⅰ		F_7,F_9 and F_{40}	19.44	2.5~3	50~1130	$\in_1c$~P_1q	892.4~1500	59~62
Block Ⅱ		F_9, F_{13} andF_{40}	40.2	4.5~6.0	250~800	Z_2dn~$P_2\beta$	475~1040	39~73
Block Ⅲ	$Ⅲ_1$	F_{13}, west branch of F_{14}, F_4, F_{41}	34.4	2.6~6.0	50~250	$\in_1c$~P_1q	528.8~1217	40~52.5
	$Ⅲ_2$	F_{13}, west branch of F_{14}, F_{41}	33.6	4.7~6.0	400~800	$\in_1q$~$\in_2d$	948.6~1756	54.6~59
Block Ⅳ		East and west branch of F_{14}	16.4	2.5~5.6	100~500	$\in_1c$~ P_1q	484~604.8	42.5~51.8
Block Ⅴ		F_4, east branch of F_{14}, F_{25}, F_{42}	100.2	2.5~5.5	0~200	$\in_1c$~D_3zg	547~729	38~49
Block Ⅵ		F_{14}, F_2, F_4, F_{31}	129.1	2.9~5.3	50~300	Z_2dn~$\in_2d$	401.~721.3	35~53

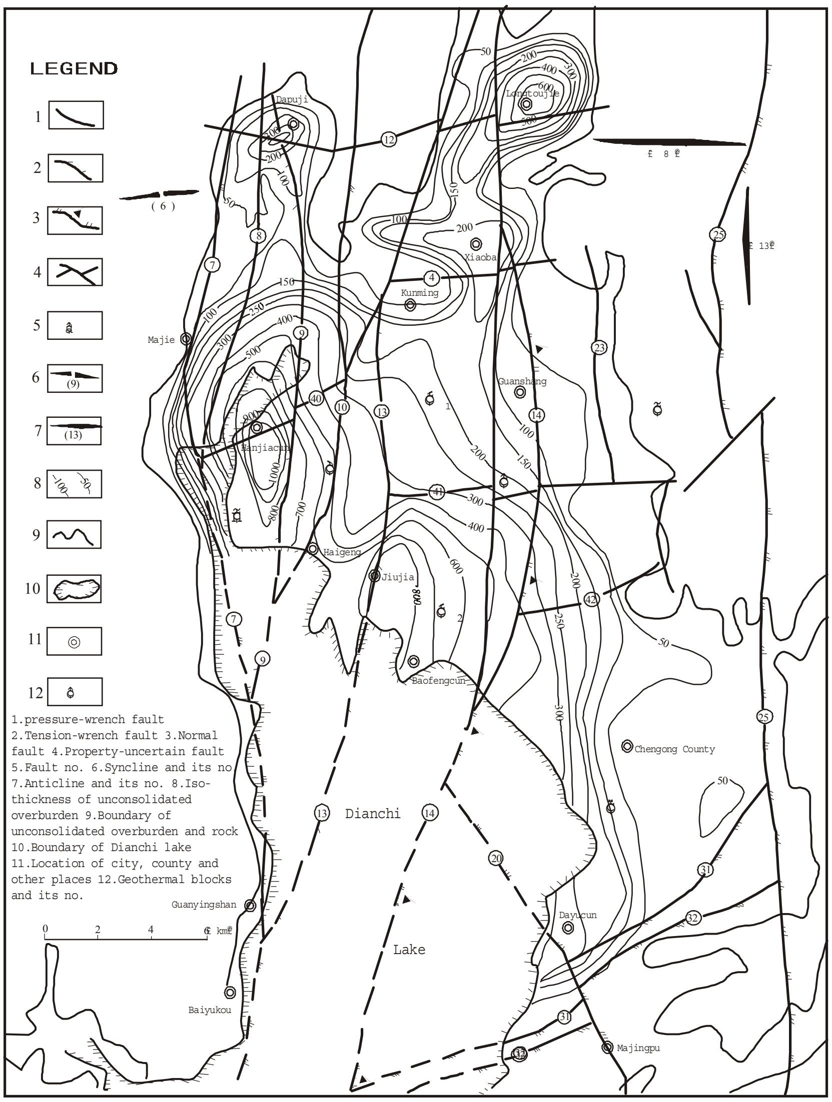
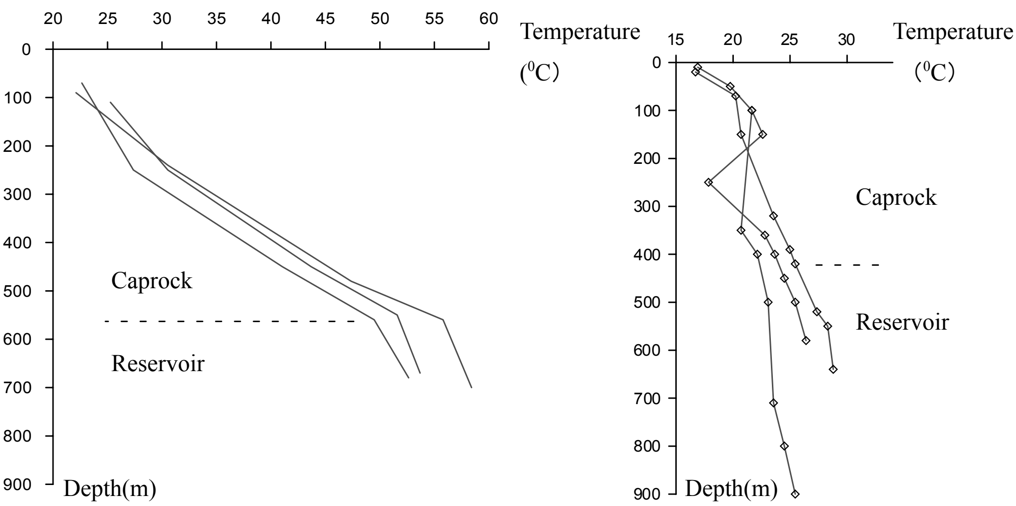


FIGURE 1: Tectonic framework and unconsolidated overburden thickness of Kunming geothermal field



(a): In the field (b): Outside the field

FIGURE 2: Formation temperature profiles measured in some wells of the field

TABLE 5: Distribution of hot groundwater chemical types

Center area		East edge	South-east edge	West edge
Block Ⅱ、Ⅲ	Block Ⅳ	Block Ⅴ	Block Ⅵ	Block Ⅰ
HCO_3-Na	HCO_3•SO_4-Na•Ca•Mg	HCO_3•SO_4-Na•Ca•Mg	HCO_3-Mg•Ca	HCO_3-Na

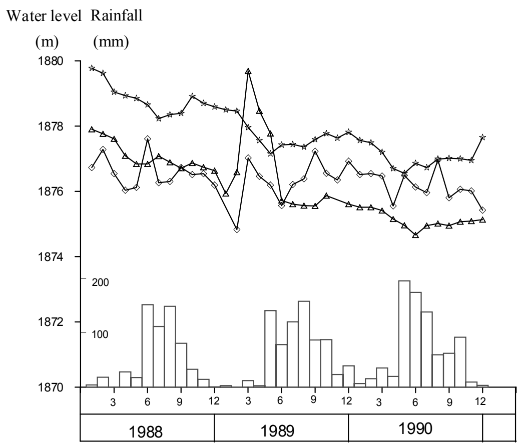


FIGURE 3: Water level observations in some wells of the field

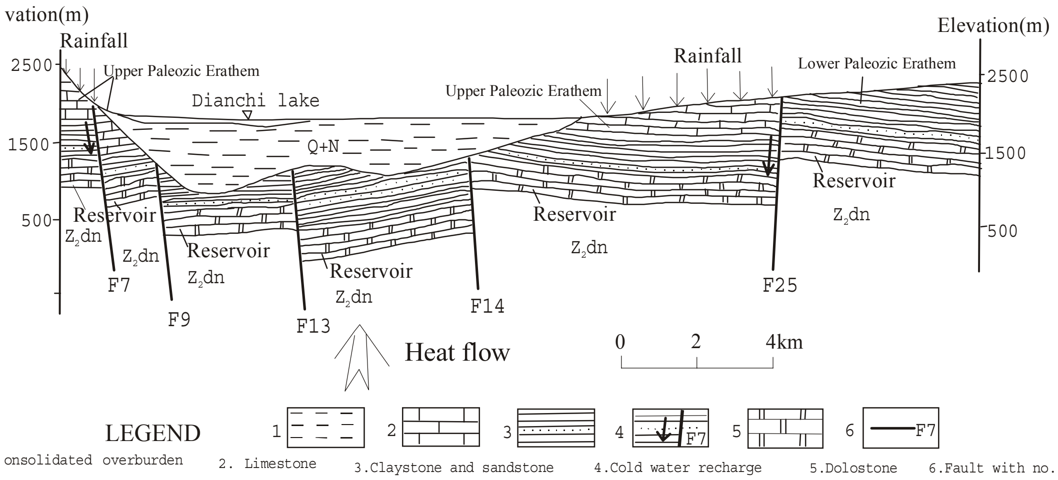


FIGURE 4: Reservoir conceptual model of Kunming geothermal field

TABLE 6: Calculated stored heat and water quantity of the field

Block NO.		Stored heat			Stored water quantity		
		Reservoir thickness (m)	Average reservoir temperature (^{0}C)	Stored heat Q_R (10EJ)	Depth of reservoir roof (m)	Depth of water level (m)	Stored water quantity ($10^9 m^3$)
Block Ⅰ		461.5	60.3	0.996	1200.0	9.8	0.314
Block Ⅱ		413.9	59.8	1.826	870.0	12.1	0.582
Block Ⅲ	$Ⅲ_1$	461.5	47.0	1.221	762.0	12.1	0.556
	$Ⅲ_2$	449.7	56.8	1.542	870.0	13.00	0.529
Block Ⅳ		461.5	48.0	0.602	700.0	13.0	0.265
Block Ⅴ		399.41	46.8	3.058	603.3	38.8	1.40
Block Ⅵ		332.04	48.1	3.418	550.0	19.21	1.50
Total				12.66			5.15