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Investigation of the Hydrothermal Potential of Different Geological Formation in the Yangtze Plate Area (YPA), China

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ABSTRACT

Thermo-physical, hydraulic property and geothermal conditions have significant effects on the potential of hydrothermal resources for a rock formation. In order to characterize the hydrothermal resources in the Yangtze Plate Area (YPA), this study investigates a sedimentary succession containing 31 rock formations that are widely distributed in YPA. Thermo-physical parameters such as density, porosity, thermal conductivity and thermal capacity of the rock formations were determined. Hydraulic conductivity was estimated by the data collected from field pumping tests. The exploitable hydrothermal resources for the rock succession were then assessed by considering the hydraulic parameters and local geothermal conditions. Finally, spatial distribution of existing hydrothermal sites is studied. The results indicate that fractured sandstone and fractured/caved carbonates are the two typical reservoir formations in this region. Claystone, siltstone, and shale are expected to have high potential as cap rocks due to the low hydraulic and thermal conductivities.

1. INTRODUCTION

Geothermal resources have become a promising resource for renewable energy in China in recent years. The usage of geothermal energy for building's heating and cooling in the Yangtze Plate Area (YPA) develops rapidly in the past decades (Zhu et al., 2015; Lin et al., 2013). There are majorly three categories of resources including the shallow geothermal resources, deep hydrothermal and hot-dry-rock (HDR) resources. The hydrothermal resource was considered to have great potential in the thermal energy supply for either district heating or power generation in YPA. The exploitable hydrothermal resources are highly decided by the local geological, hydrogeological and geothermal conditions (Antonio et al., 2016; Barbier 1997). Naturally, the heterogeneity and uncertainty of the geological units bring high risk for the exploitation of geothermal resource (Luo et al., 2014; Jeanne & Albert, 2018). Thus, the investigation and characterization of the ground conditions are of crucial importance to the assessment of hydrothermal resources.

Many previous works have been done to study the exploration and exploitation of hydrothermal resources. Youngmin et al. (2010) constructed the temperature profiles in Korea by collecting various heat flow and surface temperature data. Thermal property of the geological materials sampled from 1560 drilling holes was determined and then the accessible geothermal resources were estimated. The results showed that the geothermal resources are equivalent to around 200 times annual energy consumption in Korea in 2006. Zhang et al. (2019) estimated the hydrothermal geothermal heating in China by considering policy, technology and geological uncertainties. A model was developed to optimize investing costs for the wells with an average 1350 m depth. Nice geological scenarios with various geothermal gradient and rock permeability were discussed. It was found that those geological conditions are significant to optimize capital costs of hydrothermal heating projects.

An et al. (2016) investigated the low-medium temperature hydrothermal geothermal resource in Tianjin City, China. Different usage patterns for the shallow geothermal resources were first discussed. On the other hand, the deep hydrothermal water used for power generation was analyzed. The results indicated both underground conditions and above-ground techniques are important to the development of hydrothermal water utilization. Mauriohooho et al. (2017) used a portable x-ray fluorescence (XRF) analyzer to characterize cuttings of drilling wells in a geothermal field. The results indicated that the XRF can be applied to identify lithological boundaries and relationship between drill holes. Thus, the geologic, stratigraphic and hydrothermal conditions of geothermal reservoirs can be properly characterized.

Vidal and Genter (2011) analyzed the lithologies, temperature distribution with depth, and their hydraulic yields of 15 geothermal wells located in the Upper Rhine Graben (URG). The data showed permeability variation of the lithologies and the highest value was observed at the top of the hydrothermally altered granite. This higher permeability is likely to indicate a good connection with the reservoir which is meaningful to the exploitation of hydrothermal resources. Mielke et al. (2015) analyzed thermos-physical properties of geological materials were measured for different lithotypes by collecting the drilling cores from geothermal field in Tauhara, New Zealand. The measuring results indicated the porosity range between 30% and 45% for sediments, volcaniclastics and lava breccias, andesite lava has an average of 10% for, and rhyolite lava is about 39%. The mudstone, siltstone, breccias and lavas have similar permeability values which are lower than that of sandstone, tuff and brecciated lavas two magnitudes. Most of rock types have similar specific heat capacity values but different in thermal conductivity. It was measured the thermal conductivity decreases with decreasing porosity. Those thermos-physical parameters were found to have significant impacts on hydrothermal alteration.

The previous studies indicated that the lithotypes, thermos-physical, hydraulic property and geothermal conditions of the rocks are important factors to the evaluation of geothermal resources (Hedenquist & Lowenstern, 1994; Baba et al., 2019). The combination of geological strata plays also an extremely vital role in forming a hydrothermal system in sedimentary strata (Winterleitner et al., 2018). The investigation of thermophysical property and the stratigraphic sequence of regional rock formations are significant to characterize the hydrothermal systems. In this paper, a sedimentary succession which contains the major rock formations in YPA is investigated and the potential of hydrothermal systems for these rock formations are assessed. Thermo-physical property of the materials of the rock formations was first measured. Hydraulic property of the materials was then analyzed for both categories of clastic and carbonate rocks. The potential of hydrothermal resources by pumping water from these rock formations of the sedimentary succession was then assessed. Finally, the major findings obtained from this study are provided.

2. STUDY METHODOLOGY

2.1 Study area and stratigraphic formations

YPA covers a huge area that containing ten provinces and districts including Guangxi, Yunnan, Sichuan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang and Shanghai district in the centre and south of China, as shown in Fig. 1. The bedrocks in YPA comprise an assemblage of marine sedimentary, igneous, and metamorphic rocks. In the west of YPA, Tibetan Plateau to flow across deeply eroded mountain plateaus consisting of Paleozoic and Mesozoic rocks roughly 350 to 150 million years old. In its lower reaches, the Yangtze River flows across basin fills with Cenozoic material that is about 65 to 25 million years old. These are the result of fluvial sedimentation as the Yangtze has migrated across its lower basin throughout its Cenozoic history (Zhu et al., 2015). The whole study area covers an area of 1,480,000 km2 and has hundred millions of inhabitants.

The YPA contains rock formations with the geological ages varying from Sinian till Cretaceous period. The sampling site is located in Zigui county of Hubei province, as shown in Fig. 1. The west limb of Huangling anticline fold is selected to collect the rock blocks from the outcrops of the sedimentary succession. The Huangling anticline was formed with an axis direction of NNE and a whole sedimentary rock stratigraphic was exposed to the ground surface, as shown in Fig. 2. In the west of Huangling anticline, Zigui syncline was almost parallel set with Huangling anticline. This sedimentary rock succession contains the major rock formations in YPA. YPA has a relatively stable sedimentary environment in which the rock formations are repeatable and have similar properties (Lin et al., 2013; Zhang et al., 2013; Zhang et al., 2019). Thus, the investigation of hydrothermal potential of this stratigraphic profile is meant to understand the hydrothermal resources in the whole YPA. Fig. 2 shows the sampling profile which contains 31 rock formations.

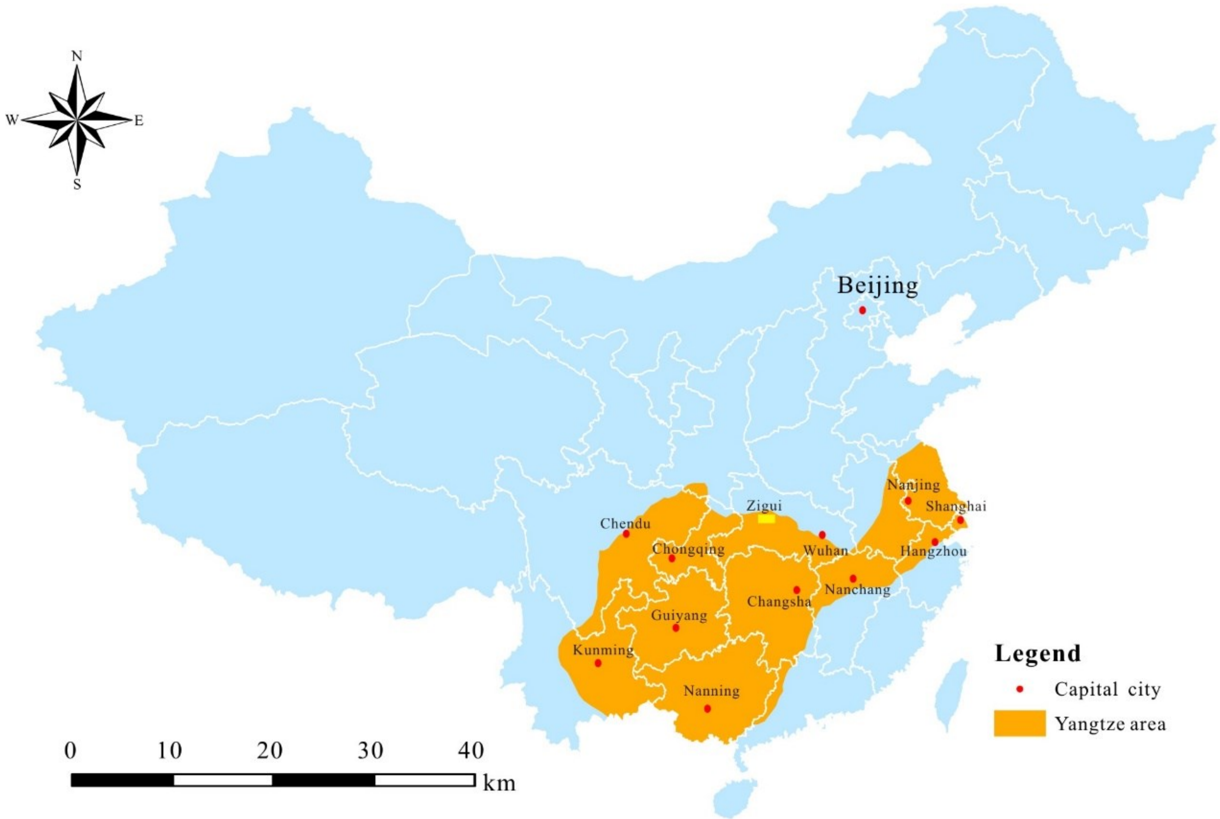


Figure 1 A map of the Yangtze Plate Area (YPA) which covers eleven provinces in the middle and south of China

Fig. 3 displays the logged geological profile of the investigated sedimentary succession in the west limb of Zigui anticline. It shows that the rock formations cover wide geological ages from Sinian till the Cretaceous period. There are about 31 major rock formations contained in the geological succession with varies lithotypes including claystone, sandstone, shale, limestone, dolomite, etc. Briefly, the lithotypes can be classified into two categories those are the clastic rocks and carbonate rocks. The clastic rocks are majorly the claystone, siltstone and sandstone, where the carbonate rocks are briefly the limestone and dolomite. Note also that the thickness of the rock formations could vary drastically from few meters to thousands meters and an average thickness of the rock formation will be considered. The property of the stratigraphic sequence of the rock formations including their thermos-physical and hydraulic properties will be determined and considered in the later assessment of hydrothermal potential.

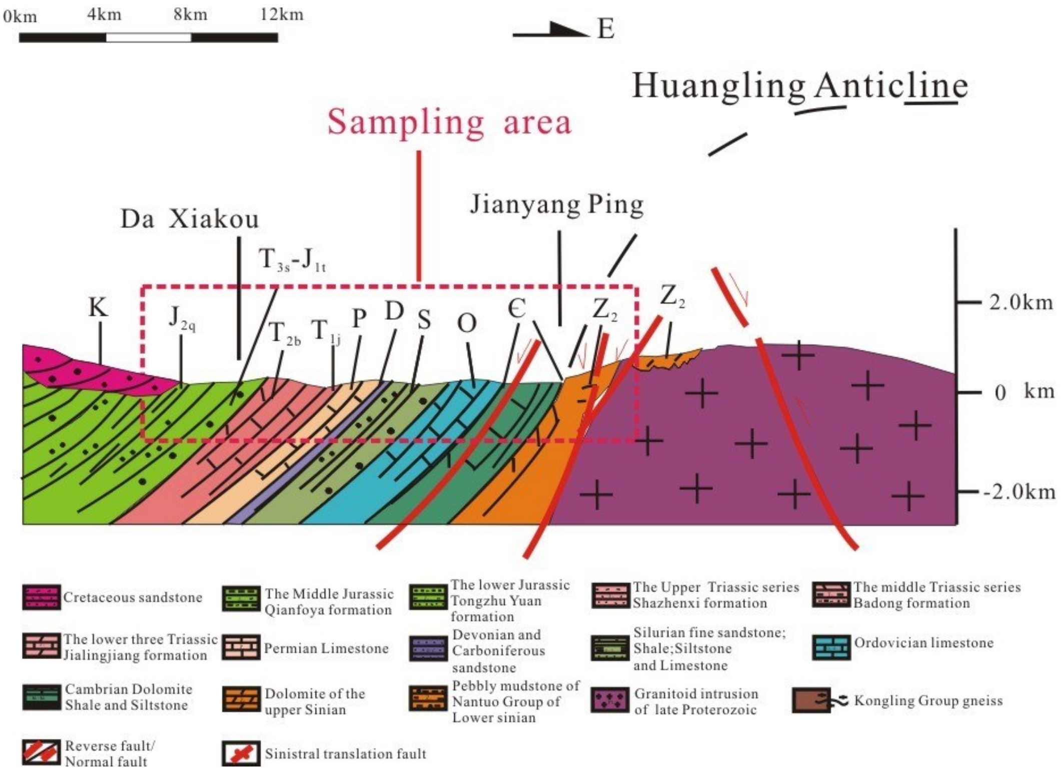


Figure 2 A geological map of the Yangtze Plate Area (YPA) and a geological profile of the west limb of Huangling anticline which is the sampling site (Luo et al., 2018)

2.2 Measurement of thermophysical property

Thermo-physical property is significant to estimate the geothermal potential of the rock formations (Wang et al., 2017). In this work 85 rock samples, each formation with minimum two and some fragile lithotypes such as claystone with three samples, are collected from rock outcrops of the west limb of Huangling anticline. In order to avoid the boundary effects in the thermal conductivity measurements, the rock blocks are cut with a size larger than 20×20×20 cm3. The physical parameters such as porosity and density have significant impacts on the hydraulic property of the geological materials. Density was determined by deploying the wax method. Thermal parameters are important to the hydrothermal reservoirs, where the materials with low thermal conductivity have good potential as the cap rocks and those ones have high thermal conductivity matches well with the requirements to form a geothermal reservoir in terms of thermal conduction. In order to determine thermal property, a portable instrument ISOMET 2114 was applied to measure thermal property of the samples. Thermal conductivity, thermal diffusivity and specific thermal capacity were determined.

2.3 Evaluation of the hydrothermal potential of the sedimentary rock formations

To exploit hydrothermal resources from a rock formation, the water is pumped from the reservoir by drilling vertical wells. A steady-state of water pumping in an aquifer system for fully penetrated well is considered. The hydraulic head drawdown of a well is highly dependent on the hydraulic parameters of the aquifer and pumping setup which can be formulated as (Jacob, 1946).

$$s_w = \frac{W}{4\pi KD}\log\left(2.25\frac{KDt_{pump}}{Sr_w^2}\right) + CW^2 \tag{1}$$

where s_w is the water head drawdown in the well (m), W is the pumping rate (m3/s), KD is Transmissivity (m2/s), t_{pump} is the time for pumping duration (s), r_w is the radius of the pumping well (m), S is the storage coefficient (-), C is the coefficient of the quadratic term of the Rorabaugh equation (m2/s5). S=0.2 is set for unconfined aquifers, t_{pump} is suggested for 200 d (Misstear & Beeson, 2000), rw is set 0.25 m, C =1900 s2/m5 as suggested by Ref. (Walton 1962).

An allowable hydraulic drawdown for pumping well can be set as follows:

$$S_w = \alpha \times b \tag{2}$$

where α is the fraction of the saturated thickness (-), b is the thickness of the aquifers (m). A 50% reduction of the saturated thickness (a=0.5), was set as suggested by Ref. (Misstear & Beeson, 2000). By measuring the flow rate of the wells, the geothermal potential for a hydrothermal well can be given as:

$$Q_p = W \times \rho_f c_f \times G_g \tag{3}$$

where Q_p is the specific exploitable resources (W/m) per single well, W is the pumping rate of well (m3/s), $\rho_f c_f$= 4.2×106 J/m3·K is the thermal capacity of water and G_g is the geothermal gradient (K/m). The exploitable geothermal resources can then be determined by known the burying depth of the reservoirs.

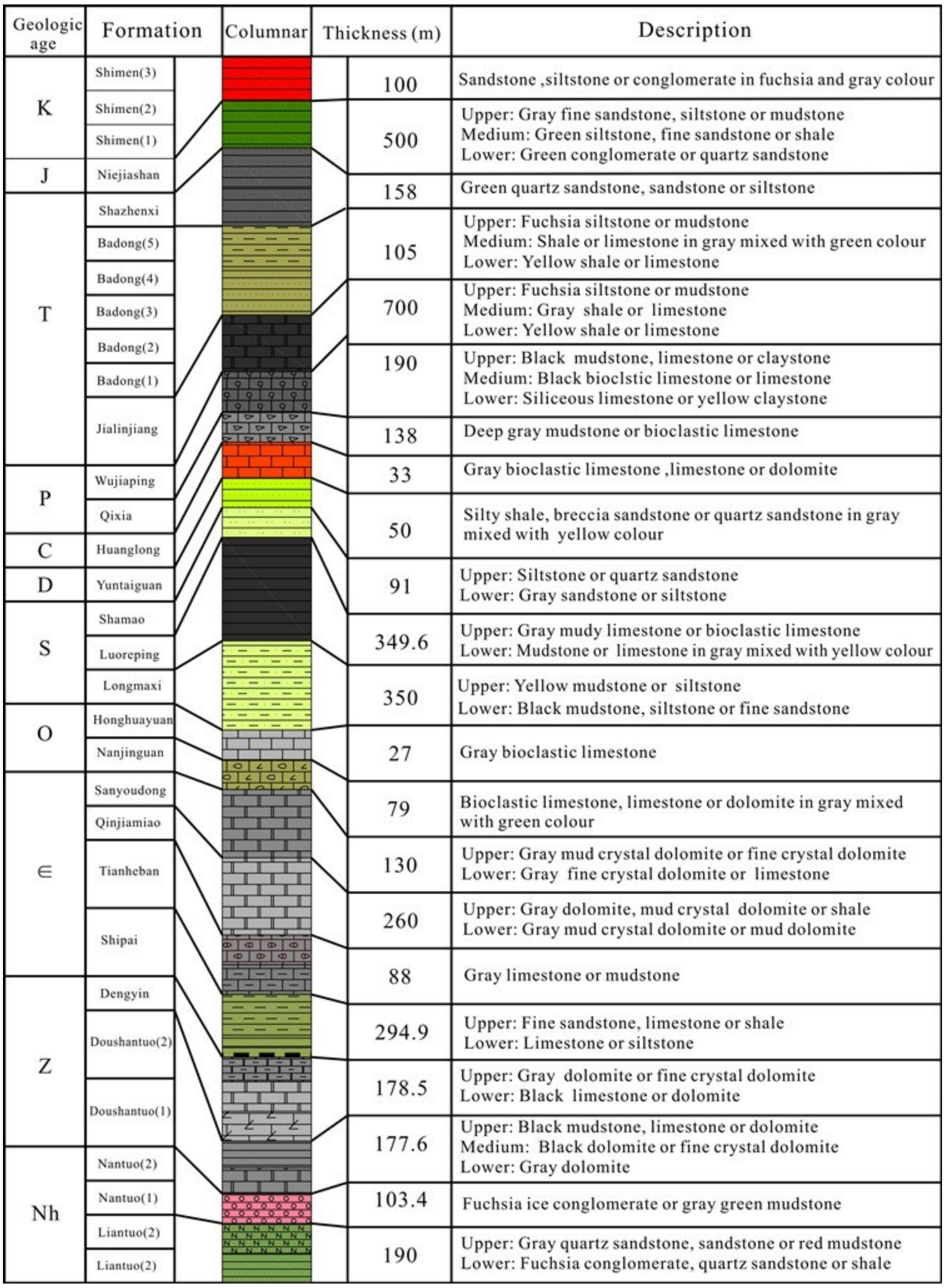
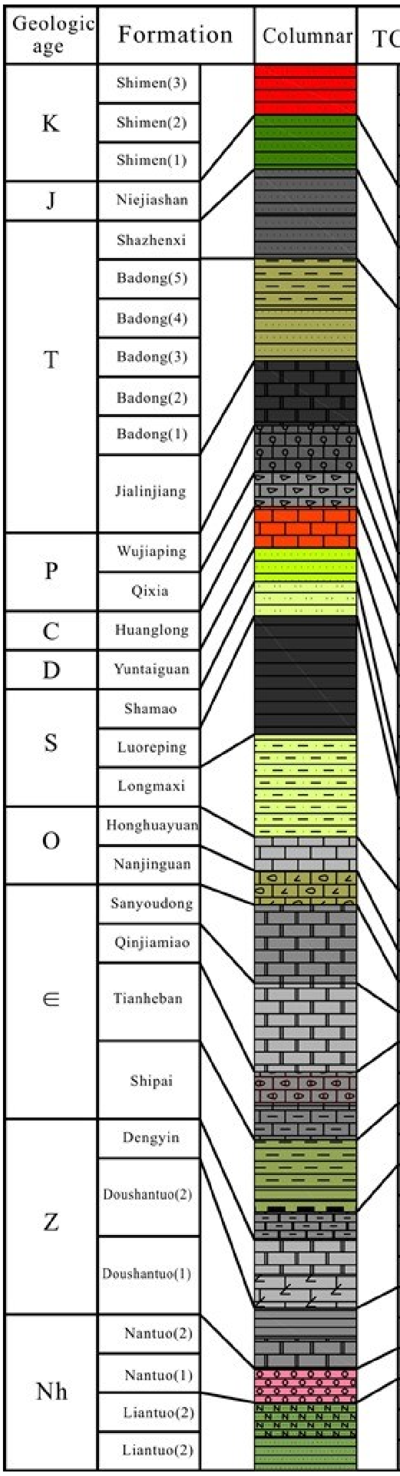


Figure 3 A geological profile shows the rock formations of the investigated sedimentary succession of the west limb of Huangling anticline in the Yangtze Plate Area (YPA)

3 RESULTS AND DISCUSSION

3.1 Thermo-physical properties

Thermo-physical property of the rock samples collected from sedimentary succession was determined. Fig. 4 displays the measuring results of the thermal conductivity, porosity and moisture content. Thermal conductivity values vary between 1.00 W/m·K and 4.47 W/m·K. The low thermal conductivity was often measured at claystone, siltstone and shale. Thus, those layers can be treated as cap rock due to the relatively low thermal transfer efficiency. While the dolomite, limestone and quartz sandstone are measured for relatively high thermal conductivity - considered to be good potential geothermal reservoirs. The density shows a small range that varies between 2.19 g/cm3 and 2.82 g/cm3. Porosity changes drastically with different geological materials. Generally, claystone, siltstone and shale have relatively high porosity, while the carbonate rocks like limestone and dolomite have lower porosity values.



TC(W/m • K)	TD(MJ/m3 • K)	Density(g/cm3)	Porpsity (%)
3.76	1.76	2.53	5.32
1.87	1.67	2.52	12.17
2.02	1.72	2.52	12.39
3.02	2.05	2.63	2.51
3.78	2.30	2.65	5.32
2.52	1.91	2.55	8.43
2.62	1.97	2.55	2.39
2.46	1.80	2.63	8.69
2.49	1.80	2.66	4.36
2.00	1.81	2.63	7.77
2.61	2.01	2.19	7.77
1.00	1.57	2.28	26.72
2.03	1.44	2.54	11.15
2.00	1.92	2.67	8.03
1.35	1.48	2.67	2.04
2.38	1.64	2.68	0.76
2.32	1.89	2.66	1.33
2.69	2.15	2.70	0.74
2.89	2.14	2.68	0.78
2.95	1.95	2.70	0.93
1.83	1.83	2.61	2.41
4.47	1.81	2.52	6.42
3.88	1.81	2.65	1.20
1.94	1.69	2.62	4.28
3.14	1.95	2.67	4.46
1.48	1.64	2.69	9.95
1.10	1.48	2.59	5.81
2.38	2.00	2.71	0.98
2.25	1.91	2.67	1.98
2.40	1.97	2.67	3.44
4.31	2.35	2.79	1.95
3.89	2.21	2.66	2.71
1.51	1.58	2.62	3.83
2.68	1.62	2.65	2.22
2.58	1.93	2.65	2.57
1.85	1.71	2.76	2.40
3.97	1.86	2.70	0.55
1.87	1.73	2.57	6.39
1.98	1.62	2.65	4.49
2.79	1.66	2.45	10.36
2.73	1.86	2.82	6.39
4.36	2.46	2.79	0.92
3.01	2.16	2.59	1.05
1.73	1.70	2.46	12.79
3.24	2.08	2.68	1.64
1.84	1.50	2.65	1.78

Figure 4 Mean value of the measured thermo-physical property of the rock formations in a sedimentary succession of the west limb of Huangling anticline in Yangtze Plate Area (YPA)

<u>Hydraulic property of rock formations</u>

<u>Clastic rocks</u>

Hydraulic property is significant to the estimation of pumping rate of a well in an aquifer. Hydraulic conductivity values of the clastic rocks were collected from field pumping tests, as shown in Table 1. It shows that hydraulic conductivity varies with different clastic formations, but all with relatively low hydraulic conductivity. It can be attributed to the natural ground could be hydraulically heterogeneous due to the fractures/caves existed in the formations. The fractures in clastic rocks have much higher hydraulic conductivity than that of the rock mass. These fractures hence govern the hydraulic conductivity of a rock formation, as it is verified in Eq. (2).

Table 1 Hydraulic property of the clastic rock formations of Huangling anticline in Yangtze Plate Area (YPA)

Geologic age	System	Lithology	Hydraulic conductivity (10-5 m/s) Field data
K	Shimen(3)	Boulder sandstone	5.24
	Shimen (2)	Siltstone	0.03
	Shimen(1)	Sandstone	2.38
		Conglomerate	0.26
J	Niejiashan	Boulder sandstone	0.03
		Sandstone	0.03
T	Shazhenxi	Siltstone	-
		Sandstone	-
	Badong (5)	Mudstone	0.035
		Siltstone	-
	Badong(3)	Calcareous mudstone	-
	Badong(2)	Calcareous shale	0.00054
	Badong(1)	Mudstone	0.035
D	Yuntaiguan	Siltstone	-
		Shale	-
		Breccia sandstone	0.97
		Quartz sandstone	0.94
S	Shamao	Siltstone	-
	Luoreping	Sandstone	-
	Longmaxi	Sandy shale	0.054
		Mud shale	0.054
O	Shipai	Claystone	-
		Carbonate shale	-
Z	Dengying	Shale	2.73
	Doushantuo (2)	Shale	2.53
Nh	Nantuo	Conglomerate	-
	Liantuo (2)	Sandstone	1.93
	Liantuo(1)	Quartz sandstone	2.97
		Sandstone	2.12

The carbonates rock was also measured of low hydraulic conductivity values with a magnitude of 10-5 m/s or 10-6 m/s by the field pumping tests those are higher than the normal laboratory data. The carbonate rocks are generally fractured and caved in the natural environment. Thus, the field data indicate that the hydraulic conductivity is dominated by the fractures and caves rather than the rock mass itself.

Table 2 The estimated dissolubility and measured hydraulic conductivity of the carbonate formations of Huangling anticline in the Yangtze Plate Area (YPA)

Geologic Age	Formation	Lithology	Hydraulic conductivity (10-5 m/s)
			Field data
T	Badong (4)	Limestone	0.035
	Jialingjiang	Limestone	0.48
P	Wujiaping	Limestone	0.23
	Qixia	Limestone	0.22
C	Hezhou	Limestone	0.99
		Limestone	1.32
		Limestone	0.99
		Limestone	16.77
O	Honghuayuan	Limestone	6.338
		Limestone	9.67
	Tongzi	Limestone	7.21
		Limestone	8.32
		Limestone	6.55
Є	Sanyoudong	Dolomite	-
		Dolomite	-
	Qingjiamiao	Dolomite	3.33
		Limestone	0.27
	Tianheban	Limestone	4.90
		Limestone	10.28
Z	Dengying	Limestone	-
		Limestone	-
		Limestone	-
		Limestone	-
		Limestone	-
		Dolomite	0.10
		Dolomite	3.45
	Doushantuo	Dolomite	-
		Dolomite	-

3.2 Hydrothermal capacity of the rock formations

Fig. 5 (a) displays the distribution of the locations for the geothermal gradient measurements in YPA. The measurements were implemented in some drilling wells randomly distributed in this region. Fig. 5 (b) shows the statistical analysis for the measured 155 geothermal gradients in YPA. It is observed that the geothermal gradients vary widely between 1.0 K/100 m and 4.0 K/100 m and are highly concentrated in the range between 1.8 K/100 m and 3.0 K/100 m, accounting for 90% of the total measured sites. The rock formations buried at 1500-2000 m depth were estimated to have a temperature varies between 42 K and 75 K by considering an annual surface ground temperature of 15 K. The reservoir temperature with varying depths will be estimated by deploying the mean value of the measured geothermal gradients.

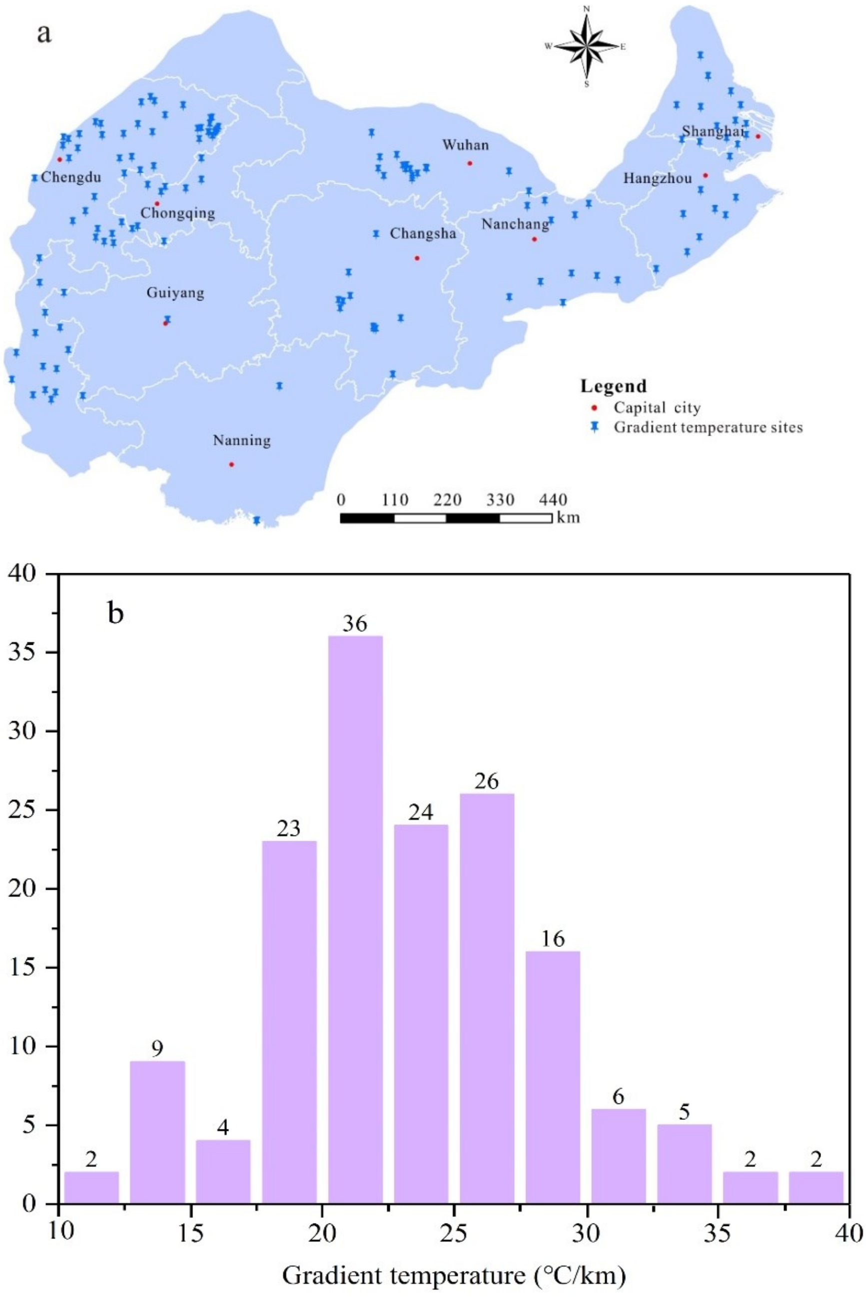


Figure 5 Distribution of the geothermal gradient measurements and statistical analysis of the measured data for 155 geothermal sites in YPA (Wang et al., 2017)

Fig. 6 shows that the assessed exploitable hydrothermal resources for the rock formation by following Eq. (4) based on data obtained from field tests. Hydraulic conductivity of the samples was measured for all the rock formations, but the field data are only limited to the aquifer layers. It shows that most of the field data are collected from the rock formation with lithotypes of sandstone, limestone and dolomite. The estimated hydrothermal resources by using laboratory data are much lower than that of the field data. The higher exploitable hydrothermal resources of the field data can be attributed to the high hydraulic conductivity of the natural layers than that of the collected rock samples. This can be caused by the heterogeneous of the natural rock formation such as the fractures and karst caves contained in the rock layer those have very high hydraulic conductivity values. The high hydraulic conductivity values govern the effective hydraulic conductivity of the whole layer or reservoir, as shown in Eq. (2).

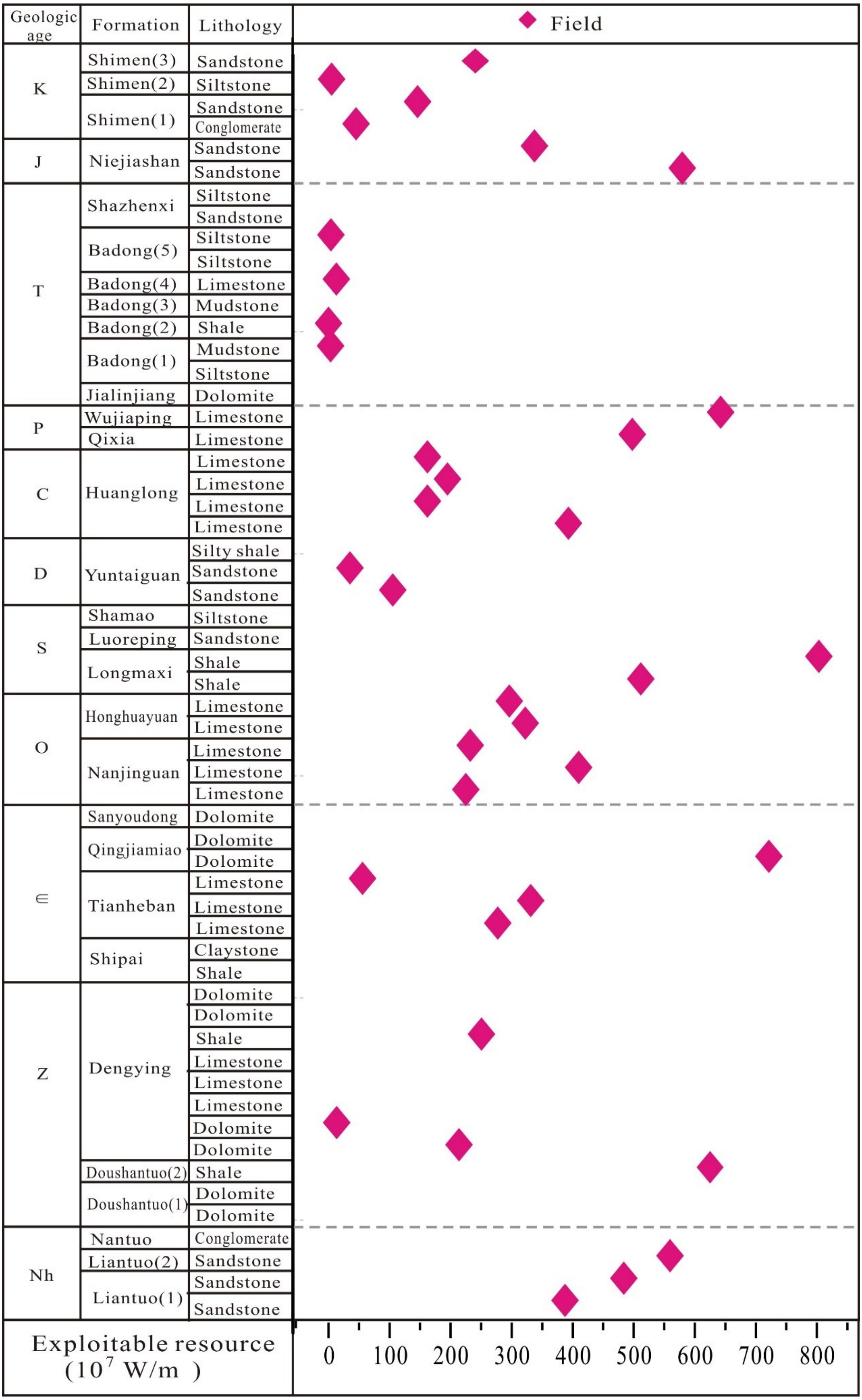


Figure 6 The estimated potential of the exploitable hydrothermal resources for the major rock formations in the Yangtze Plate Area (YPA) (Geological Survey of Anhui province, 2013; Geological Survey of Zhejiang province, 2013)

3.3 The distribution of the existing hydrothermal sites

The data for the geothermal sites in YPA was collected and analyzed. Fig. 7 displays the spatial distribution of natural hot spring and artificial geothermal sites. It shows that the natural hot spring is highly concentrated around the faults. Most of the faults are with strike direction of NNE in this region. There are two main fault zones one is located in the west of YPA that transverse Yunnan, Guizhou, Chongqing and Hubei provinces, the other one across Guangxi, Hunan, Jiangxi and Zhejiang province those are located in the eastern parts of this region (Wang et al, 2017; Zhang et al., 2013). On the other hand, the artificial hydrothermal sites are highly distributed around provincial capitals which have high density of inhabitants. This indicates that the location of artificial hydrothermal sites is highly dominated by energy demand. Moreover, it implies also there are many rock formations can be treated as potential hydrothermal reservoirs in the sedimentary rock succession and those are widely distributed in YPA.

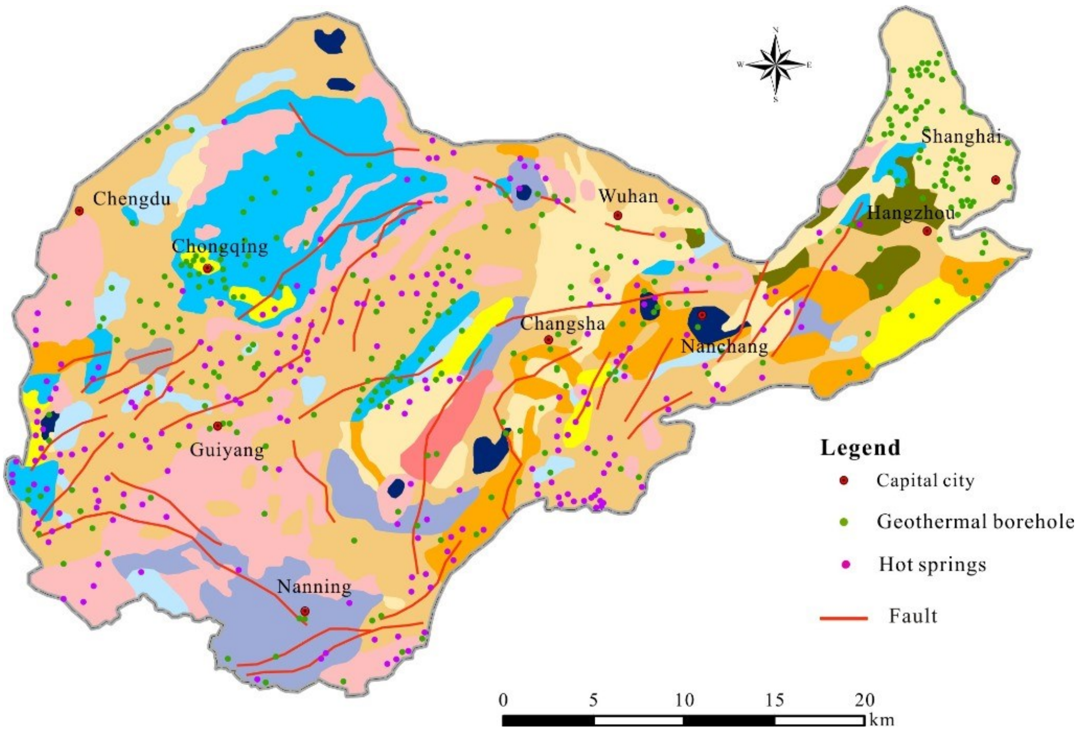


Figure 7 The distribution of the hydrothermal exploration sites for both the natural hydrothermal sites and drilled hydrothermal wells in the Yangtze Plate Area (YPA)

4 CONCLUSIONS

This paper investigates the potential of hydrothermal resources of a sedimentary succession which contains the major rock formations in YPA. Thermo-physical property of the collected rock samples of 31 geological formations was determined and analyzed. The hydraulic conductivity was measured to assess the hydraulic property of the rocks specimens. Then, the potential of exploitable hydrothermal resources of these rock formations by water pumping from drilling well is assessed based on the hydraulic property data collected from field pumping tests, and the local geothermal gradient. Finally, the spatial distribution of the existing geothermal sites is studied. Major findings obtained from this study are provided as follows:

Thermo-physical property: Thermal conductivity of the rock formations with different lithotypes varies between 1.0 W/m·K and 4.47 W/m·K. The rock formations such as sandstone, limestone and dolomite generally have a high thermal conductivity which represents high heat transfer efficiency. The rocks such as claystone and siltstone are measured of low thermal conductivity and these rocks are considered to have good potential as the cap rocks in terms of thermal conduction. The hydraulic conductivity was also determined for the clastic and carbonate rocks. Data collected from field pumping tests shows that the effective hydraulic conductivity for aquifer layers was 10-5 m/s or 10-6 m/s. It implies that the natural ground could be hydraulically heterogeneous due to the fractures and caves existed in the rock formations.

The exploitable hydrothermal resources were assessed by considering the water pumping out from the formations based on hydraulic parameters measured by field pumping tests. It shows obviously the geothermal resources estimated by the field pumping data is with high potential of the hydrothermal resources. The analysis of spatial distribution of hydrothermal sites shows that the natural hot springs were highly adjacent to the fault which provides the main path for the discharging of deep confined geothermal water. While the artificial geothermal drilling wells are highly concentrated in provincial capitals which have high density of inhabitants, indicating an area with high energy demand. The reservoirs have high hydraulic and thermal conductivity, and cap rocks are often with low hydraulic conductivity and low thermal conductivity. Thus, the potential reservoir layers are the rock formations such as caved/fractured carbonate rocks or the fractured sandstone formations. Most of the claystone, siltstone and shale formations can be treated as potential cap rocks in this region.

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