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Main Achievements in Ningbo Mid-eastern Volcanic and Non-anomaly Region During Deep Geothermal Exploration

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ABSTRACT

Ningbo, who belongs to continental volcanic zone of Zhejiang Southeast region, its geothermal exploration is basically a blank area. In order to meet the development of the local economy, a lot of work has been performed by geologists recently including successfully drilling geothermal wells in Dragon Lake and East Lake which fill in deep volcanic geothermal development gaps of Ningbo eastern regions: seven to eight geothermal wells were drilled during 2004 in Shenzhen, Ninghai country, Ningbo, of which four were successful, and the largest one has more than 1000 m^3 water per day; the first deep well was drilled with 1230m, 41.5℃ and 252m^3 water everyday, in Xi'ao, East Lake area in 2006;Also in the cover about 3000m thick volcanic of Dragon Lake area, a geothermal well with 2000m was completed in March 2012.

The study area is the eastern part of Ningbo, and this article is based on the Ningbo – Shenzhen geothermal area, locating in the fourth tectonic unit called Xinchang- Dinghai fault uplift, and covered by pyroclastic rocks (tuffaceous siltstone) and a small amount of lava from Cretaceous to Jurassic strata basically within several kilometers underground. With low porosity, very weak permeability, low thermal conductivity of rock, these formations can be a good cap rock with superior insulation properties. Temperature gradient is around 2.8℃/100m in the area. It is more difficult to find layered reservoir due to its non- geothermal anomaly. Therefore the key choice is to find out thermal conductivity and heat faults.

Although volcanic rocks are distributed throughout the study area, it has been indicated that the origin of geothermal doesn't concern with volcanic rocks and might be subject to deep geothermal exploration theory. Higher porosity formations or faults have been acknowledged based on the geophysical methods to confirm the geothermal reservoir structure. This paper puts emphasis upon several methods, such as Controlled Source Audio-frequency Magnetotelluric(CSAMT), Radon and Mercury Measurement and High-precision Gravity Measurements, which played an important role in exploring geothermal in Dragon Lake area. Integrated geophysical methods are much better on Searching for geothermal than a single geophysical method in this region. It manifests enriching the extraction of geological and abnormal information, improving the accuracy of interpretation by single geophysical method, reducing the false judge about anomalies, and enhancing geothermal exploration outline for the study area for the future.

Indicating the chemical type, this analysis is combined with chemistry data, such as geothermal wells, springs, and surface water, confirming the origin of geothermal fluid, explaining hydrogeochemical characteristics by some features of ion, and estimating geothermal reservoir temperature by geothermometer method. Through the geothermal resource assessment, including release of heat, water quality and water use, we predict hot water migrated to the surface mixed with cold water and the geothermal temperature was in the low level, small and medium geothermal field. Hot water can be used as medical care, bath and so on. Meanwhile by speculating higher occurrence of hot temperatures in deep formation, this area has some prospect of development of geothermal resources.

1. INTRODUCTION

It is so difficult to find layered reservoir in the study area that is covered by thick Jurassic volcanic rocks, and the key point is to find faults with water and thermal conductivity. Just as its volcanic distribution but non- geothermal anomaly area with temperature gradient around 2.8℃/100m, the geothermal exploration in this region might not be associated with volcanic rocks, which accords with the theory of deep bedrock on the contrary. We are sure of anomaly range with integrated geophysical methods as reference for similar geological environment. The development of geothermal fills in geothermal blank in this area. After evaluating geothermal reserves and water quantity, we find there is certain potential about geothermal development in Ningbo mid-eastern volcanic and non- anomaly geothermal area. So we must continue to expand geothermal area, which not only will increase local tourism, but also save energy and reduce emission.

2. SITE CONDITIONS

The study area is located in the forth tectonic unit called Xinchang – Dinghai fault– uplift. Formation in the study area is basically volcanic rocks (tuffaceous – siltstone) and a small amount of lava from Jurassic to Cretaceous in the depth of few kilometers, which can constitute a good seal condition with generally low porosity, very weak permeability, and low conductivity of rock. Permeable crack grows when fracture cuts through impermeable strata. As long as the crack reaches a certain scale, the loop channel of under groundwater will appears while it will accept cold water recharge and get heat supply from deep cycle. Zhenhai-Shenzhen fracture is a major shear fracture trending NNE, and the fault is the channel to heat source which is identified from the presence of hot springs along it. The fracture trending NNW with tensile and shear properties, can be distinguished by its permeability and connectivity, meeting the condition of fractured geothermal reservoir. Heat mainly comes from long-lived radioactive decay in the earth's crust..

3. INTEGRATED GEOPHYSICAL METHODS

It's more effective to adopt a variety of integrated geophysical measurements in an area just as Dragon Lake area, such as (CSAMT), Radon and Mercury Measurement and High-precision Gravity Measurement, which played an important role in exploring geothermal.

As shown in Figure 1，Fg1, Fg2 faults judged by the gravity bouguer anomaly curve all pass through the points of fastest rising or fastest falling, namely the extreme points in horizontal gradient, which basically correspond to the high values of radon and mercury measurement. For example, the minimum horizontal gradient value appears far from western end of 350m in bouguer anomaly curve 1st, which corresponds to the highest field of the 14th point in radon and mercury measurements.

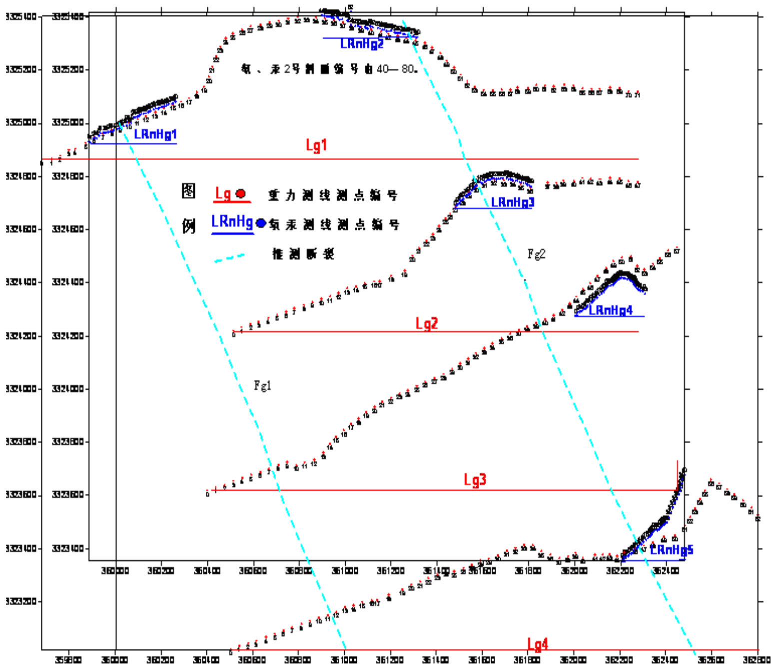

Figure 1: Achievements integrated by Radon and Mercury and High-precision Gravity Measurements in Dragon Lake.

Anomaly points of Radon and Mercury following the F3 fracture explained by CSAMT, are interpreted as a group of small faults trending NNW, shown in Figure 2. They are perhaps F3 fault, but scattered broken bundles in the shallow underground.

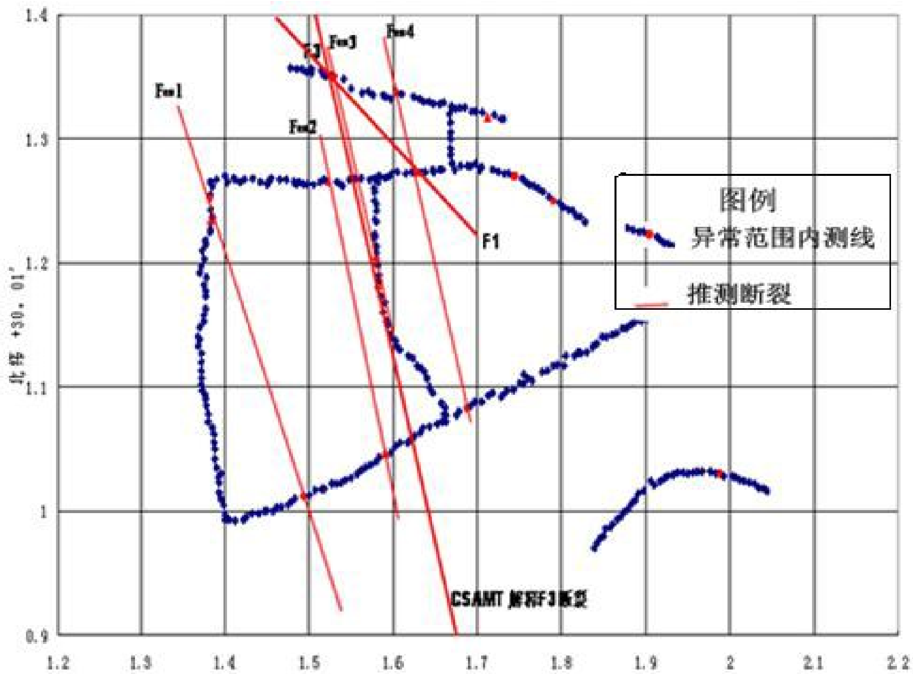

Figure 2: Achievements integrated by Radon and Mercury and CSAMT Measurements in Dragon Lake in Dragon Lake.

We can speculate anomalies distribution of gravity, mercury and radon and CSAMT shown a certain consistency from Figure 3. The extreme point in the first derivative curve of gravity appears at 350m and 1800m, which corresponds to the value of high field in radon and mercury, and the low resistivity discontinuities in the 6th CSAMT line occur at zones of 300m～600m and 1350m～1600m. This indicates that these two places are abnormal distribution of the fracture, and validates the reliability of three geophysical methods to find faults structure. Thus we can delineate geothermal anomaly range in Dragon Lake area.

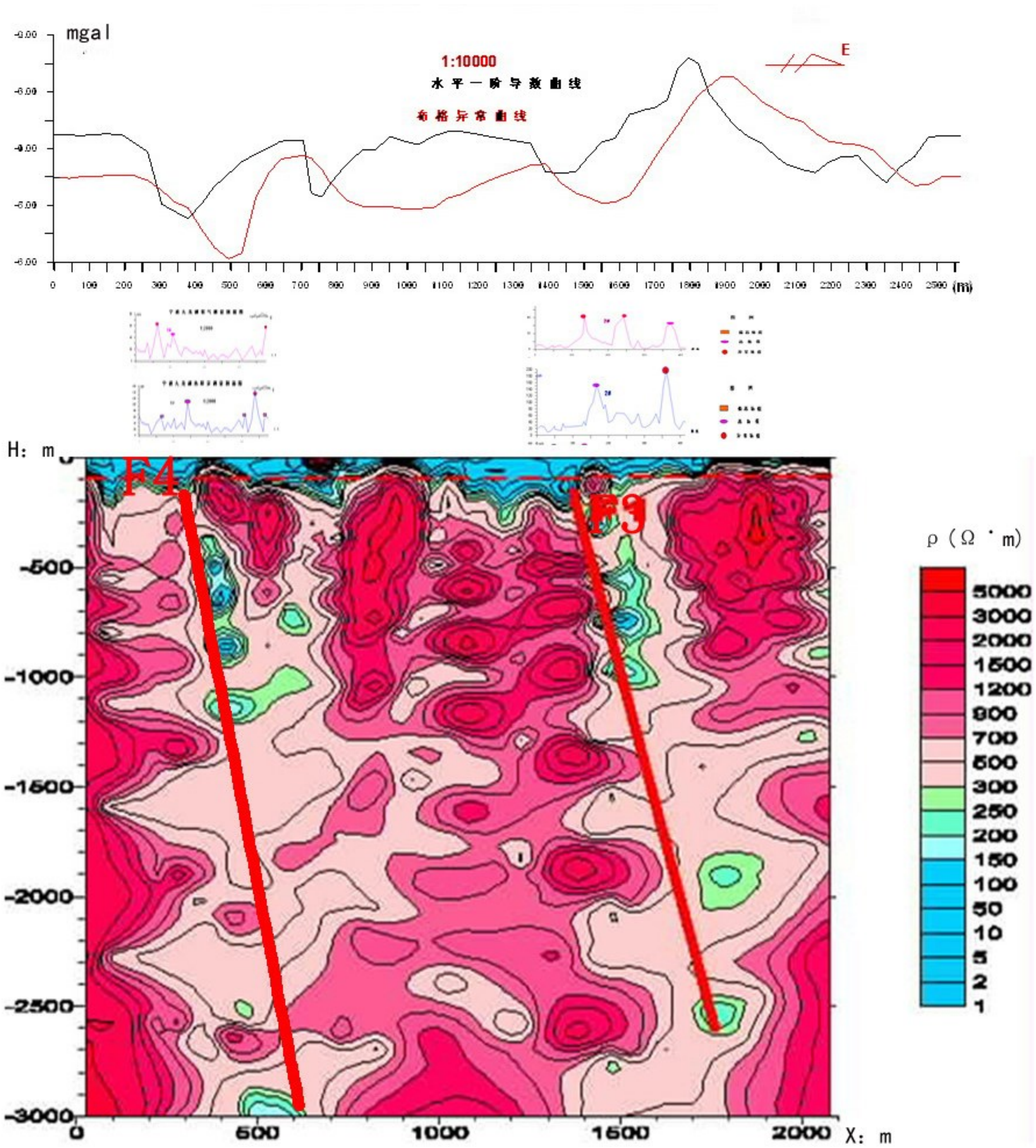

Figure 3: Achievements integrated by High-precision Gravity, Radon and Mercury and CSAMT Measurements in Dragon Lake

4. HYDROGEOCHEMICAL ANALYSIS

We collect chemistry data of the water samples in recent years (shown in table 1).This will help for geothermal prospect and temperature forecast if we analyze chemistry type and calculate geochemical geothermometer for the water samples. Objectively speaking, it is difficult to completely analysis the chemical characteristics lack of rare elements and isotope data, but still a reflection of regional rule of chemical characteristics.

4.1 Chemical Characteristics

It is a common hydrogeochemical method to simply and intuitively show the relationship between eight ions in Piper three-line diagram (Figure 4).

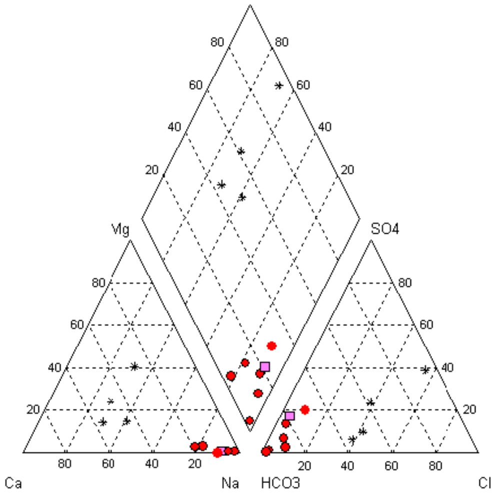

Figure 4: Piper three-line diagram(black asterisks indicating surface water, red circle indicating geothermal water, purple boxes representing spring water)

Three of surface water points fall upper left in the diamond, whose cations are mainly Ca^{2+} and Na^{+}, and the anions mainly HCO_3^- and Cl^-, so surface water chemistry type is HCO_3·Cl-Ca·Na. The points of geothermal water and hot springs all fall below the diamond, with chemical types all HCO_3-Na since dominant cation and dominant anion are Na^+ and HCO_3^- respectively.

We made Lange Montreal - Ludwig diagram in order to intuitively distinguish chemical compositions of hot water and surface water (shown in figure 5). Geothermal water and hot springs water samples lie in Pink area of the upper right corner, and surface water samples distribute at the blue area of the bottom left corner. We can see the anion of geothermal water and surface water is closer to HCO_3^-. Therefore, we can consider the geothermal in Ningbo mid-eastern volcanic area originates from precipitation, no bearing on magma and volcanic.

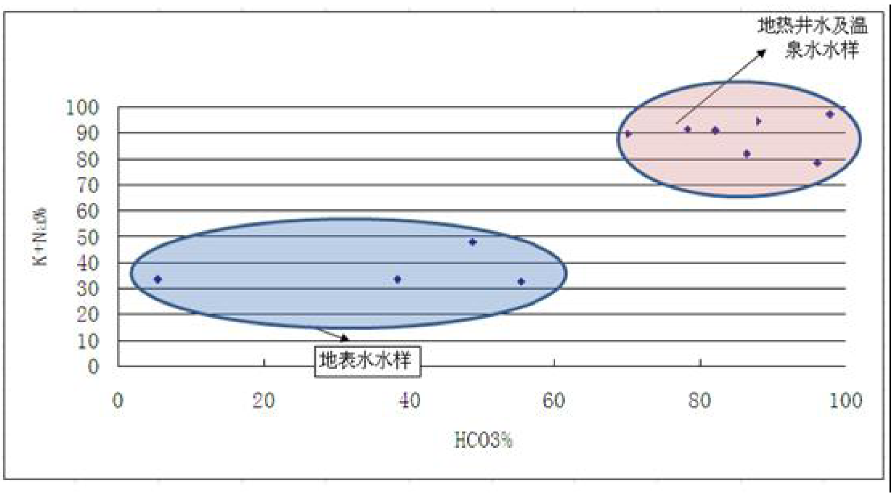

Figure 5: Lange Montreal - Ludwig diagram

4.2 Geochemical geothermometer

Potassium and magnesium and silica geothermometer are usually suitable for the application of cryogenic geothermal. Potassium and Magnesium geothermometer that is also called "the touched temperature in drilling", represents reservoir temperature of not too deep underground. The higher temperature it is, the more favorable of reservoir condition is. The formula is:

$$t=\frac{4410}{13.95-\lg(C_2^2/C_3)}-273.15 \quad (1)$$

where t, C_2, C_3 are potassium and magnesium geothermometer, content of potassium and magnesium in water, respectively.

Silica geothermometer: it stands for some temperature in which such content of silica can be dissolved in deep underground. The higher temperature of silica geothermometer shows that reservoir condition held on a favorable environment. The silica in hot water is formed of dissolved quartz, and the water is not boiling when it reaches the sampling area (wellhead or vents), the formula can be used as following:

$$t=\frac{1309}{5.19-\lg C_1}-273.15 \tag{2}$$

With *t* silica geothermometer, and C_2 content of Silica.

The computing results are in the following table:

Table 1:temperature of geothermal reservoir calculated by geothermometer of water samples in study area

No.	1	2	3	4	5	6	7
Location	Xi'ao 1	Xi'ao 2	Dragon Lake 1	Zhen 2 hole $_a$	Zhen 2 hole $_b$	C_1 well	Shenzhen spring
Actual temp(°C)	41.5	50.1	63.5	47	47.4	34.7	47
SiO_2 geothermometer (°C)	75.41	60.94	66.01	95.94	107.17	82.09	70.42
K/Mg geothermometer (℃)	84.05	59.50	64.75	91.7	—	59.75	73.61
Average geothermometer (°C)	79.73	60.22	65.38	93.82	—	70.92	72.02

As can be seen from table 1, the temperature of geothermal reservoir in study area ranges from 60□C to 107□C, which belongs to low-medium temperature. But the actual drilling shows that the calculated geothermometer is higher than the actually measured temperature. On the one hand geothermometer represents the highest temperature that hot water once reached in circulation, and on the other hand the fewer water samples in study area lead to erroneous results of calculating geothermometer without considering water-rock interaction balance. But it can be speculated that the geothermal water was mixed with precipitation in the course of transportation to surface, while higher temperature geothermal may also appear in deep strata, so it will have some prospects for the development of geothermal resources in the study area.

5. RESOURCE EVALUATION

We calculate the heat emissions and heat storage of geothermal wells, and analysis the potential of Ningbo volcanic geothermal. Evaluation of the quality of geothermal resources can be recommendations for the rational use in the future.

5.1 Geothermal resources calculation and evaluation

We use natural heat release to estimate heat by geothermal resources based on low level of geothermal exploration in the study area according to《The evaluation method of geothermal resource》(DZ40-85).The equation is as following:

$$Q_w = 365Q\rho_w C_w (t_w - t_0) \tag{3}$$

Where Q_w, Q, ρ_w, C_w, t_w, t_0 are respectively, heat release by geothermal wells per year(J/a), flow of geothermal wells(m^3/d), water density, specific heat of water, bottom-hole temperature, and reference temperature.

Table2: heat release by geothermal wells in study area

No.	Flow (m^3/d)	Specific heat (J/kg °C)	water density (kg/m^3)	temperature (°C)		heat release by wells		
				Bottom- hole	Reference	heat release (10^9J/a)	Folded fuel (t / a)	
							Standard coal	Oil
Xi'ao 1	256	4186.8	992.8	41.5	16.2	9826	335.3	234.7
Xi'ao 2	62.8	4186.8	993.2	50.1	16.2	3230	110.2	76.0
minor total	--	--	--	--	--	12056	445.5	310.7
Dragon Lake 1	810	4186.8	995.9	63.5	16.2	58309	1989.5	1391.6
Total	--	--	--	--	--	71365	2435	1702.3

We take Dragon Lake and East Lake into a geothermal field. The heat underground is assumed to be ten folds of nature based on the method according to 《Geological evaluation of geothermal resources》(DZ40-85) to determine geothermal reserves of this geothermal field.

The total heat of known geothermal reserves in volcanic geothermal field is 71365×1010J/a, equivalent to standard coal 24350t/a and petroleum 17023t/a.The total calories is 71365×1012J if its service life is one hundred yeas, which is equal to about 22.63MWt, belong to small-medium geothermal field.

5.2 Water quality and evaluation

Hot water temperature is 40 ~ 60 ℃, and chemistry type is HCO3-Na with total dissolved solids generally less than 1.0g / L, pH about 7.4 to 8.0, and slightly alkaline. The range of SiO_2 content is 21.4 ~ 56mg / L, and F- is 1.18 ~ 20 mg / L. It plays a certain role in medical effect, and can promote blood circulation and eliminate skin tension in bathing. Hot water is not suitable for drinking without defluoridation just as F-levels were all≥ 1.0 mg / L.

6. CONCLUSIONS

We successfully drilled hot water with several geophysical methods to detect buried fault and look for deep geothermal reservoir. Such methods with cost-effective identification should be promoted in the study area, which will play a multiplier effect especially for finding underground water within the activity and deep fault zone. There are some prospects for the development of geothermal resources in the study area, and we should control exploration initiatively about geothermal resource.

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