Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Occurrence Mechanism and Geothermal Exploration Model of Low-Medium Temperature Convective Geothermal Systems in Jiaodong Peninsula

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Keywords: Jiaodong Peninsula; Heat controlled and water conducted Structure; “V” shape structure; Occurrence mechanism

ABSTRACT

Jiaodong Peninsula is rich in geothermal resources. However, due to the lack of mature theory to guide the exploration, there is a large number of drilling wells that are "heat without water" or "water without heat" found in the process of geothermal drilling. A systematic method or guidelines for the exploration of geothermal resources has still yet to be established. Thus, this paper comprehensively analyzed the mechanisms of geothermal resources in Jiaodong Peninsula on the basis of 1) geothermal geological survey of the 15 hot springs, 2) heat conducting faults and water transmitting faults analysis, 3) temperature measurement, 4) distribution characteristics of geothermal fields and reservoir and drilling data analysis of 15 geothermal fields. 12 artificial geothermal deep wells were used to test our hypothesis. Based on the above analysis, we concluded that the geothermal resources in Jiaodong Peninsula are mainly distributed in the “V” shape area where the hanging wall of the NE- and NW-trending faults intersect to each other. The geothermal reservoir is controlled by the NE- and NW-trending faults and has an irregular columnar shape. Its geo-temperature field is also controlled by the geothermal fluid flow field and the geothermal reservoir morphology, that the distribution is "Π" shape. According to these conclusions, we proposed a "V" shape model of heat controlled and water conducted faults, and clarify the mechanism of deep geothermal resources in Jiaodong Peninsula. Our work provides a theoretical basis for the exploration of the deep geothermal resources in Jiaodong Peninsula.

1. INTRODUCTION

Jiaodong Peninsula is one of the regions with the most abundant low-medium temperature convective geothermal resources in the eastern coastal areas of China. However, in addition to the natural hot springs that have been exposed, people encounter many technical problems in the process of drilling for new geothermal resources. The biggest problem is that during the drilling process, there are a lot of wells which are “water without heat” or “heat without water”, which causes many boreholes to become “abandoned holes”. Based on the previous research and taking the Jiaodong Peninsula as an example, this article systematically studies the mechanism of the occurrence of low-medium temperature convective geothermal resources in Jiaodong Peninsula and innovatively proposed a conceptual model suitable for geothermal exploration in Jiaodong area. Jiaodong Peninsula is located on the northwest side of the collision edge between the Pacific Plate and the Eurasian Plate, its tectonic unit has undergone many stages of structural deformation in the long geological history. Especially since the Mesozoic, the tectonic activity of the Pacific plate resulted in strong and frequent sub-brittle faults in the surface, they are characterized by multi-period, inheritance and different mechanical properties. These structural traces constitute a structural combination of different eras, different hierarchy, and different properties, which overlap, cross-cut, and constrain each other, forming the structural pattern of NNE or the NE-trending and the NW-trending fault in Jiaodong Peninsula.(Song, 2009; Zhang et al, 2007; Li et al., 2004) (Figure 1), the extensive distribution of Mesozoic intrusive rocks and structures not only provided conditions for the formation of large gold deposits in Jiaodong area (Niu et al., 2011), but also provided heat sources and channels for the formation of geothermal resources. Through the distribution characteristics of coastal geothermal resources such as Jiaodong Peninsula, Fujian province (Deng 2017; He et al. 1999), Guangdong Peninsula (Yuan, 2013; Wang, 2018) and Yunnan Peninsula (Cheng, 2008), we can find that the faults is the main factor controlling the distribution of geothermal resources in the eastern coastal areas of China (Wang, 1993). Jiaodong hot springs are mainly exposed at the intersection of the anticline core and multiple sets of faults, and belongs to low-medium temperature convective geothermal resources, the movement of geothermal fluid is strictly, the natural hot springs are exposed at the intersection of the NNE or the NE-trending fault and the NW-trending fault where is a “X” shape area(Jin et al, 1999), the fractures in these locations are very developed and the rocks are much more broken, the approximate columnar reservoir channel formed by the intersection of the water-conducting fault and the heat-conducting fault becomes the most favorable upward flow channel for the geothermal fluid. However, in the process of drilling wells to explore geothermal resources in Jiaodong, because there is no correct geothermal resource occurrence mechanism, simply relying on geophysical methods to determine the location of geothermal drilling has brought huge economic losses to people. In this paper, taking the geothermal field in Jiaodong Peninsula as an example, the study on the occurrence mechanism and the prospecting model of convective geothermal resources in the low-medium temperature is not only beneficial to the exploration of geothermal resources in Jiaodong, but also useful for the exploration of geothermal resources of the same type in other parts of China.

2. REGIONAL GEOTHERMAL GEOLOGICAL BACKGROUND

2.1 Regional geological tectonic background

The Jiaodong Peninsula is located in the North China Stratigraphic Area, the Ludong Stratigraphic division, and the exposed strata include the Middle Archean Tangjiazhuang Group, the Neoarchean Jiaodong Group, the Paleoproterozoic Jingshan Group, the Fenzishan Group, the Zhifu Group, and the Neoproterozoic Sinian Penglai Group and the Mesozoic Cretaceous Laiyang Group, Qingshan Group, Wangshi Group and the Cenozoic Paleogene Wutu Group, Neogene Linyi Group, Quaternary volcanic accumulation and loose accumulation. The magmatic rocks in the area are very developed, especially the granitic rocks are widely distributed. The Precambrian basement rocks and granitoids with high thermal conductivity are widely exposed, and the sedimentary caprock with low thermal conductivity is missing, which is beneficial to the formation and exit of hot springs. (Xiong, 1984; Li et al, 1997) (Fig.1).

The tertiary structural units in the study area mainly include: Jiaobei uplift, Jiaolai basin and Weihai uplift. The main structural traces include Rushan-Weihai anticline, Qixia anticline, Jiaolai syncline, etc. The anticline structure is a "ridge-type" with a narrow upper and wide lower, which is beneficial to the lateral migration of geothermal fluid and refraction and redistribution (Zhao et al, 2017). The overall strike of the faults is consistent with the stress effect on the edge of Eurasian plate and Pacific plate and is easy to cause earthquakes (Deng et al., 1999; Chen et al., 2004; Zhang et al., 2007), among them, NE and NNE trending faults are mainly compressive faults and torsional faults, which mainly conduct heat, NW faults are mainly tensional or tensional-shear faults, which mainly conduct water (Lv et al., 2007).

Figure 1: Regional geological map

2.2 Current status of regional geothermal drilling

In this study, 12 artificial geothermal deep wells in Jiaodong area were investigated and pumping tests were carried out. The results of the water conductivity coefficient and the recoverable resources are shown in Table 1. It can be seen from the table that there are four geothermal deep wells with recoverable resources less than 100 m^3/d and one less than 250 m^3/d. These geothermal deep wells can't meet the requirements of geothermal resources development and belong to "abandoned wells" for geothermal development. The main reason for the occurrence of many "abandoned wells" in the Jiaodong area is that the mechanism of the occurrence of geothermal resources in the Jiaodong area is not well understood. This paper studies the deep geothermal characteristics and the occurrence mechanism of 15 natural hot springs and 12 artificial geothermal deep wells in Jiaodong area and clarifies the mechanism of deep geothermal resources in Jiaodong area, further narrowing the scope of geothermal well drilling, thus effectively improve the success rate of drilling.

Table 1: Depth, Temperature, Transmissivity and flow rates of geothermal wells in Jiaodong Peninsula

Location of artificial geothermal deep well	Depth /m	Temp/℃	T/(m²▪d⁻¹)	Q/(m³▪d⁻¹)	Location of artificial geothermal deep well	Depth /m	Temp/℃	T/(m²▪d⁻¹)	Q/(m³▪d⁻¹)
Yudaishan spring, Yantai city	1200	32	16.2	638.60	Nanguan Village, Longquan Town, Yantai City	1200	29	66.6	2444.51
Sanatorium of Yantai Shengli Oilfield	2200	28	0.65	33.41	Liugong Island, Weihai City	1500	32	8.4	367.59
Cishan spring, Yantai Development Zone,	1500	33	9.00	387.08	Foguang Garden , Longkou City	652	25	2.00	90.73
Majiagou Village, Penglai City	1500	32	10.00	411.67	Bi Guiyuan, Haiyang City	1200	32	8.00	341.61
Lijing Garden , Longkou City	600	28	0.24	12.67	Xia Guang Tourism Company, Qixia City	1200	13	5.00	224.05
South of Anli Reservoir, Qixia City	1200	30	3.00	432.00	Fang Yuan Company, Haiyang City	1500	28	1.00	36.48

3. OCCURRENCE CHARACTERISTICS OF GEOTHERMAL RESOURCES

3.1 Geothermal geological features

Till now, 15 natural hot springs have been discovered in the Jiaodong Peninsula. The hot springs mainly expose the axis position of the Jiaodong uplift area and the symmetric extension areas on both sides, such as river terraces, floodplains and coastal plain areas. Most of the hot springs are exposed on the tectonic fracture zone covered by the Quaternary loose rock layer (the cover layer is generally thin). The liquid temperature at the wellhead is mainly between 40 and 90 °C. The closer to the axis of the uplift, the higher the liquid temperature at the wellhead of the geothermal field, and the salinity is between 0.45 and 7.69 g/L. All the springs belong to the low-medium temperature geothermal resources, the outcropping location of hot springs is mainly controlled by regional deep faults and secondary faults near the outcropping location.

Table 2: Geothermal geological characteristics of natural hot springs in Jiaodong Peninsula

Name of spring	Wellhead temp /℃	Salinity mg/L	Main fracture of the hot spring	Name of spring	Wellhead temp /℃	Salinity mg/L	Main fracture of the hot spring
Baoquan Tang	67	5660	NW-trending Shendaokou fracture ;NE-trending Jinxiandiing fracture	Longquan Tang	59	542	NE-trending Tangxi-Longquan fracture
Wenquan Tang	59	1221	NW-trending Wenquantang fracture ;NE-trending Xizicheng-Baojiashan fracture	Yujia Tang	46	445	NE-trending Taocun fracture、Guocheng-Jimo fracture；NW-trending Yujiatang fracture
Hongshuilan Tang	71	830	NE-trending Hengkou-Dongliulin fracture	Xingcun Tang	28	557	NE-trending Zhuwu fracture
Qili Tang	66	741	NE-trending Hengkou-Dongliulin fracture ;NW -trending Baolonghe fracture	Dongwen Tang	62	7686	NE-trending Qingdao fracture; NE-trending Guocheng-Jimo fracture
Hulei Tang	60	1014	NE-trending Qinglonghe fracture; NW-trending Tangxi fracture	Aishan Tang	52	796	NE-trending Zhaili-Yangchu fracture
Tangcun Tang	51	5741	NE-trending Changyanghe fracture; NW-trending Tangcun fracture	Wenshi Tang	54	1435	NE-trending Cunliji fracture NW-trending Wenshitang fracture
Daying Tang	62	1760	NE-trending Mishan fracture; NE-trending Dianliyuan fracture	Dong Tang	81	3312	NE-trending Linglong fracture; NW-trending Zhaoping fracture
Xiao Tang	56	2509	NE-trending Xianguding fracture				

The natural hot springs in the study area are generally exposed in the relatively low-lying riverbed, river-level terraces and coastal plains. The elevation of the outcropping position is generally low, especially the Baoquan Tang, which is basically the same as the sea level. That because the hydrostatic pressure is relatively low in low-lying areas, it is beneficial to the upward movement of groundwater after deep circulation heating to form a hot spring which recharge from a relatively high mountainous area. The mineralization degree of different geothermal fields is quite different, such as Baoquan Tang, Tangcun Tang, Dongwen Tang and Dong Tang is larger than 3.0g/L, or even 7.7g/L. However, the mineralization degree of geothermal fields such as Yujia Tang, Qili Tang and Aishan Tang is less than 1g/L. The difference is quite large, which is closely related to whether the geothermal field is recharged by sea water or the water-rock interaction in its runoff pathway. Regionally, there are regional deep and large faults near hot springs in Jiaodong which are mainly NE- trending heat conducting faults, and secondary NE-trending faults and NW-trending faults are also widely distributed near the exposed location of the geothermal field, among which regional deep and large faults are the main factors controlling deep migration and heating of geothermal fluids. Local NE and NW faults are the decisive factors controlling the surface outcropping of hot springs. Regional deep faults are the main factors controlling the deep migration and heating of geothermal fluids, while NE-trending faults and NW-trending faults near the exposed location of the geothermal field are the decisive factors controlling the exposed location of the hot springs.

3.2 Distribution characteristics of geothermal field and reservoir

To the low-medium temperature convective geothermal resources, the thermal field distribution characteristics can not only reflect the distribution characteristics of geothermal field reservoir on the plane, but also reflect the vertical spatial distribution characteristics of geothermal field reservoirs (Luan et al., 2002; Zeng et al, 2017), and by the horizontal and vertical distribution characteristics of the thermal field can better understand the spatial distribution characteristics of geothermal field reservoir. Here we take Dongwen Tang hot spring as an example to analyze the thermal characteristics of the geothermal field in Jiaodong Peninsula. Fig.2 shows the horizontal and different depth of the reservoir distribution in Dongwen Tang, it can be seen from the figure that with the increase of the reservoir depth, the distribution of the reservoir on the horizon becomes smaller and smaller. That mainly because the closer to the surface, the more fragmented of the reservoir and wall rock, especially in the loose Quaternary strata, the wider diffusion range of geothermal fluids, however with the increase of the reservoir depth, the narrower of the reservoir channel.

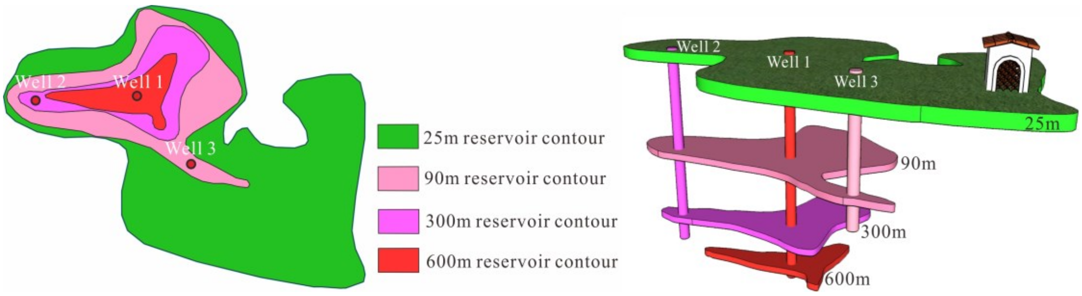

Figure 2: Horizontal and different depth of the reservoir distribution in Dongwen Tang

Fig.3 is the temperature profile of Dongwen Tang hot spring. From Fig.3, it can be seen that the higher temperature near the intersection of the faults, the lager the influence of reservoir on the surrounding thermal field. The uplift direction of isotherm indirectly represents the distribution of reservoir and geothermal fluids, which is similar to "Π" shape.

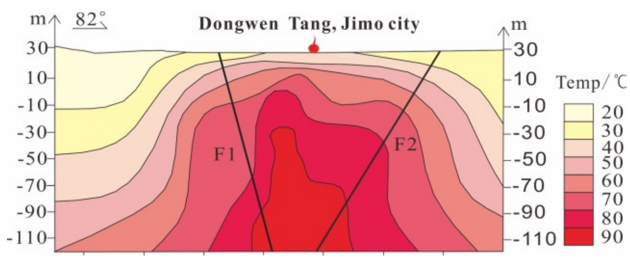

Figure 3: Temperature profile of Dongwen Tang hotspring

3.2 Distribution Characteristics of Geothermal Fields

In this study, detailed geothermal geological surveys were carried out on 15 geothermal fields in Jiaodong Peninsula`. It was found that the geothermal fields in Jiaodong were exposed in the “V” shape area where the NE-trending fault upper plate intersects with the NW-trending fault hanging wall. The zone formed by the intersection of huge faults is the channel for geothermal fluid storage and upward migration. In the process of deep geothermal drilling, the area of the lower plate of the fault should be avoided. Taking the Yujia Tang geothermal field as an example to show the model of "V" shape of heat controlled and water conducted structure.

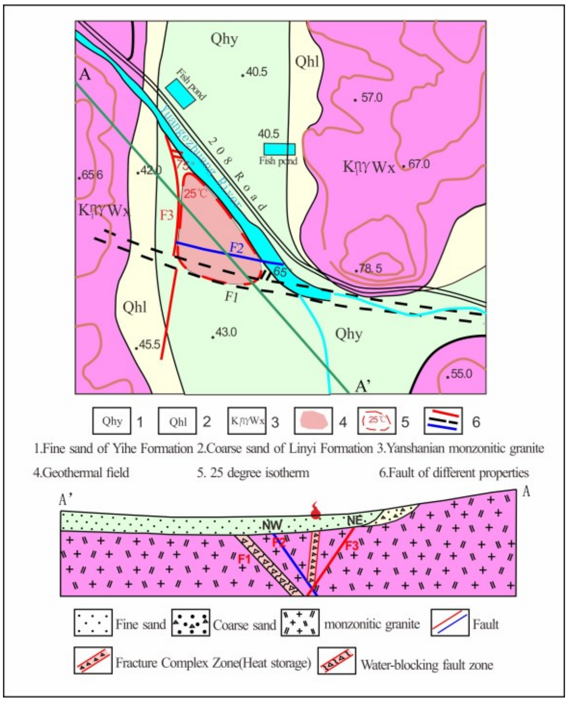

Figure 4: Geology of the Yujia Tang geothermal field

From Fig.4 it can be seen that the lithology of the geothermal field is relatively simple, mainly distributed the Monzogranite from the late Yanshanian of Mesozoic. The surface of the geothermal field is also distributed with fine sand of the Weihe Formation and gravel coarse sand of the Linyi Formation. There are three main faults controlling the geothermal field. F1 is the main fault zone in this area. Its strike is NWW and tends to NE, the inclination is between 60° and 70°, the width is about 20 m, and there are breccia, fault mud and extruded lenticle in the fault zone, which is a water-blocking fault; F2 fault strike is also NWW, tending to the north, the width is about 10 m. It is a secondary fault of the F1 fault which is a water-conducting fault. F3 fault is a NNE-oriented compression-torsion fault, the occurrence is steep and tends to SE, and the fault is a heat-conducting fault. The high-permeability fracture zone formed by the intersection of F2 and F3 faults provides a channel for the upflow of the geothermal fluids, which forms the heat reservoir channel of the Yujia Tang geothermal field. In this study, we define the boundary of geothermal field by the 25 °C isotherm circled by the borehole temperature measurement. It can be seen from Fig.4 that the geothermal wells in the geothermal field are mainly distributed in the north of F2 and the west of F3, the geothermal resources in Yujia Tang mainly distributed in the "V" shape area where the hanging wall of the NE- and NW-trending faults, there is no obvious geothermal anomaly at the foot wall of F1 and F3.

In order to further illustrate that the geothermal resources of Jiaodong Peninsula are mainly exposed in the "V" shape area where the hanging wall of the NE- and NW-trending faults intersect, the paper systematically shows the distribution of other typical geothermal resources in Jiaodong Peninsula. Fig.5 shows the location and range of the representative geothermal field in the Jiaobei uplift area and the Jiaonan-Wendeng uplift area in the Jiaodong Peninsula., it can be seen that Hongshuilan Tang, Wenshi Tang, Daying Tang, Xiao Tang et al all are exposed in the "V" shape area, however, there no hot springs in the foot wall of the fault.

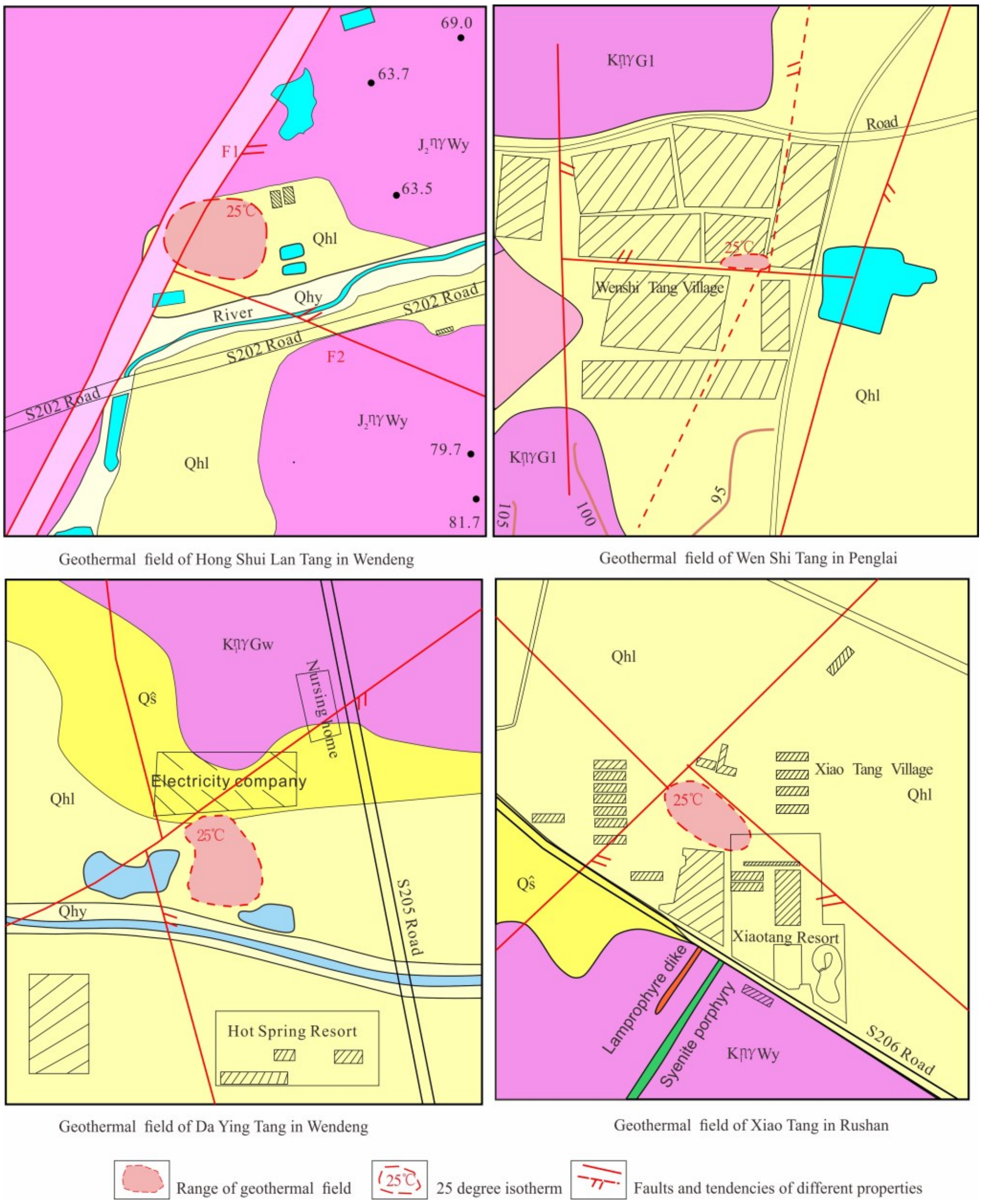

Figure 5: Distribution range of representative geothermal fields in Jiaodong Peninsula

Since the geothermal fields in the Jiaodong Peninsula are mainly controlled by the NE-tending torsional thermal-conducting fault and the NW-tending extensional water-conducting fault. The reservoir channel is usually a high-permeability water-conducting channel formed by the intersection of two or more faults, the shape of the channel usually is banding, which is not like the layered geothermal field, the range of the reservoir channel is very small. Because of that, it's difficult to drilling a new well successfully in Jiaodong Peninsula. Therefore, in the process of geothermal resource exploration, in addition to clarifying the location of the water-conducting fault and thermal-conducting fault, it is also necessary to determine the location and tendency of the reservoir channel, this is the key to determining the success or failure of geothermal resources exploration in Jiaodong Peninsula. We generalize the reservoir space shape of geothermal field in Jiaodong Peninsula to a similar columnar reservoir with a certain tendency which is formed by the NE tending thermal-conducting fault and the NW tending water-conducting fault, the tendency of the channel is controlled by the tendency of the faults. So before the drilling, we need to use the geophysical methods to determining the position and occurrence of the faults, and then use the occurrence of the faults to estimate the depth and morphology of the reservoir channel, it can effectively guide the exploration of deep geothermal resources.

4. CONCEPTUAL MODEL

In order to analyze the occurrence mechanism of the 15 geothermal fields in Jiaodong Peninsula, the model of "V" shape of heat controlled and water conducted faults is established (Fig.6). The hot springs in the study area belong to the low-medium temperature convective geothermal resources, controlled by widely distributed faults in Jiaodong, especially the hot springs are exposed in the "V" shape area where the NE-trending fault upper plate intersects with the NW-trending fault hanging wall, the intersection of the two groups of faults forms a more fractured zone, providing a high permeability channel for the migration of geothermal fluids (Zhang et al., 2017). Usually, NE-trending and NNE-trending faults cut deep, and communicated with the deep heat source of the crust and even the upper mantle, which became the channel for the deep heat to upflow fast; NW-trending faults are mainly water-conducting, the atmospheric precipitation and the surface water flow into the ground by the tiny faults in the recharge area, with the underground off of the ground water, the ground water migrate to the deep crust. During migration, the cool ground water continuously absorbs heat from wall rock and thermal-conducting fault and undergoes water-rock reaction with wall rock, then the heated geothermal water moves upward along the columnar channel formed by the intersection of thermal-conducting and water-conducting fault under the action of buoyancy (Yang et al, 2009), the geothermal fluid that migrates upwards overflows in low-lying and low hydrostatic pressure areas to form hot springs. The survey found that the Jiaodong geothermal field reservoir can be generalized into an approximate columnar reservoir in a certain direction as follow: the main channel for geothermal fluid migration, the lithology of the reservoir and wall rock all are monzonitic granites except Dongwen Tang, the reservoir cap is thinner and less than 40m, the lithology of the cap mainly are sand and clay. The model fully demonstrates the process of recharge, runoff, heating and excretion of geothermal fluids in the Jiaodong Peninsula.

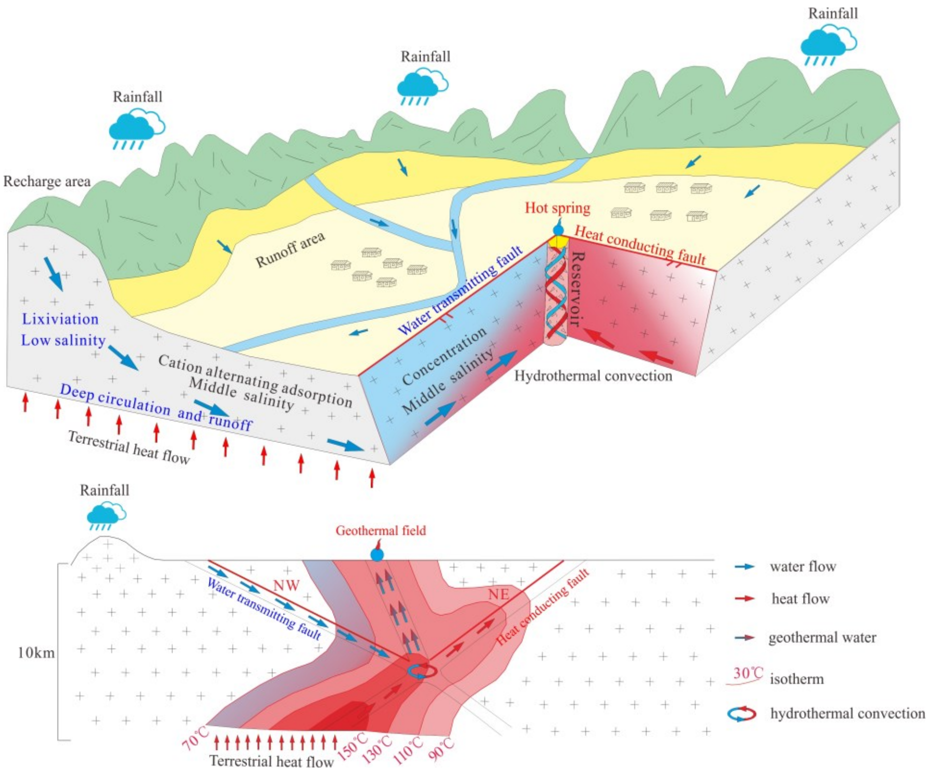

Figure 6: Conceptual model of "V" shape of heat-controlled and water-conducted faults

5. CONCLUSION

(1) The Jiaodong geothermal field is mainly exposed in the low-lying areas such as the riverbed, the river terrace and the coastal plain area in the axis of the Jiaodong uplift, the temperature of the geothermal fluids gradually decreases from the axis to the both sides; The reservoir is mainly controlled by NE-trending fault and NW-trending fault, which can be approximated to a columnar reservoir with certain tendency, the lithology of the reservoir and wall rock are mainly monzonitic granites; Thermal field is affected by the distribution of reservoir space and the geothermal fluid flow field, the shape of the thermal field is similar to "П" shape, the spatial distribution of the thermal field reflects the spatial distribution of reservoir.

(2) Geothermal fields in the Jiaodong Peninsula are mainly controlled by the NE-tending torsional thermal-conducting fault and the NW-tending extensional water-conducting fault. On the plane, the geothermal resources are mainly exposed in the “V” shape area where the hanging wall of the NE- and NW-trending faults intersect; In vertical, the upper of the reservoir is wide and the lower is narrow, the spatial extension direction of the reservoir is jointly controlled by the tendency of the faults, the deep geothermal prospecting is mainly to determine the location and depth of the deep reservoir space.

(3) Based on the analysis of 15 geothermal fields, this paper propose a "V" shape model of heat controlled and water conducted faults, which means that the geothermal resources in Jiaodong Peninsula are mainly distributed in the “V” shape area where the hanging wall of the NE- and NW-trending faults intersect, the NE-trending faults cut deep, and communicated with the deep heat source of the crust and even the upper mantle; NW-trending faults are mainly water-conducting, which provide the channel for ground water to runoff, heating and upflow. The establishment of the model has guiding significance for the exploration of deep geothermal resources in the Jiaodong Peninsula.

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