Frontiers in Power and Energy Systems (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/fpes.2024.030102
ISSN 2516-2926 Vol. 3 Num. 1

Research Status and Prospect of Marine Geothermal Energy—Taking China's Ocean as an Example

Jiangtao Tan[1,a,*], Jialong Yu[1,b]

[1]Tibet University, Lhasa, Tibet, 850000, China
[a]164378130@qq.com, [b]2529244806@qq.com
[*]Corresponding author

Keywords: Marine Geothermal Energy, China Ocean, Development Trend

Abstract: As the largest part of the earth, the ocean is rich in energy resources. Marine geothermal energy, as a renewable and clean energy, has great potential and importance. However, the current research on marine geothermal energy is relatively lacking. The main geothermal research is still concentrated on land, and the potential of marine geothermal energy has not been fully explored. As one of the largest coastal countries in the world, China has many sea areas, including the East China Sea, the South China Sea, the Bohai Sea and the Yellow Sea. These sea areas not only have abundant biological resources, but also contain abundant marine geothermal energy resources. In these sea areas, geothermal resources such as submarine hot springs, hydrothermal channels and underground hot rocks are abundant and have great energy potential. This paper focuses on the research status of marine geothermal energy in the four major sea areas along the coast of China, systematically summarizes the geological survey and geothermal resources of the major sea areas, and looks forward to the future development trend. This paper discusses Marine geothermal resources, development technology, application field, sustainability and environmental protection, so as to arouse more people's attention and research on Marine geothermal energy.

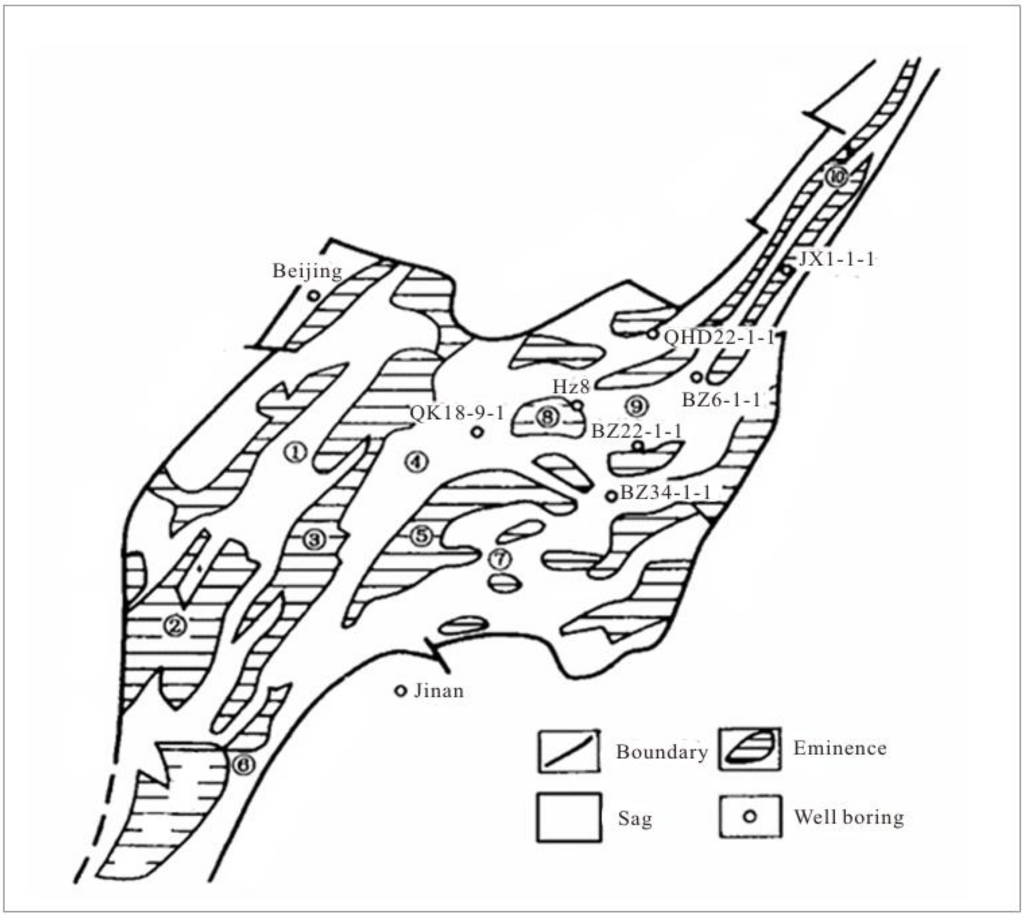
1. Introduction

In order to cope with the energy crisis and ecological crisis since the 20 th century, the search for alternative clean energy has received more and more attention. Among them, geothermal energy is the only renewable clean energy that is not affected by weather and seasonal changes. It is widely used in power generation, greenhouse cultivation, aquaculture, recuperation-bathing and heating. Because of its large reserves, high energy utilization efficiency, low operating cost and energy saving and emission reduction, it is one of the important breakthroughs in the field of new energy. [1-2]. China has a vast sea area, which is adjacent to China 's land, mainly including the East China Sea, the South China Sea, the Bohai Sea and the Yellow Sea. These sea areas are directly connected with China's land. In the current situation of relative shortage of resources, it is of great significance for China's economy, security and national defense to find out the resources of marine geothermal resources and explore the development direction of marine geothermal energy.

2. Research Status of Marine Geothermal Energy in China

2.1 Research Status of Geothermal Energy in Bohai Sea

The Bohai Sea is located in the eastern part of the Bohai Bay Basin, with an area of 7.2×10^4 km^2, accounting for 1 / 3 of the total basin area. According to the regional location, the Bohai Sea can be divided into five blocks: Liaodong Bay, Bodong, Bonan, Boxi and Bozhong. The Bohai Bay Basin is an area affected by multiple fault activities. These fault activities have gradually formed an uneven geological structure pattern with alternating uplifts and depressions. The specific situation can be referred to Figure 1. [3].



①Jizhong Depression ②Xingheng Uplift ③Cangxian Uplift ④Huanghua Depression ⑤ Chengning Uplift ⑥Linqing Depression ⑦Jiyang Depression ⑧Haizhong Uplift ⑨Bozhong Depression ⑩Liaohe Depression

Figure 1: Regional tectonic setting of Bohai Bay Basin (Hu Shengbiao, 2000)

Since the 1980 s, a large number of scholars have conducted in-depth research on the geothermal field and thermal history of the Bohai Sea. Chen Moxiang et al. [4] analyzed and discussed the geothermal conditions in the shallow crust of the Bohai Sea. It is concluded that the geothermal in the Bohai Sea is distributed in a high-low band, the geothermal gradient of the cap rock is related to the depth of the bedrock surface, and has a relatively high geothermal background value. Hu Shengbiao et al. [5] used terrestrial heat flow measurement, apatite fission track and vitrinite reflectance data to restore the thermal history of Bohai Sea Basin. The results show that the Bohai Sea Basin experienced a high heat flow (heat flow value of 70-90 mW / m^2) stage before 25 Ma.

Since then, the thermal state of the Bohai Sea Basin has shown continuous cooling. Gong Yuling et al. [6] studied the geothermal field of the Bohai Bay Basin, and obtained that the average geothermal gradient of the Bohai Bay Basin was 34.7 ℃ / km, and the average heat flow value was 64.4 mW / m^2. Qiu Nansheng et al. [7] studied the distribution characteristics of the geothermal field in the Bohai Sea, reflecting the control of the basement on the heat flow. Han Dong et al. [3] estimated the total heat stored in the Cenozoic thermal reservoir by using the thermal reservoir volume method to be 4.5 $\times 10^{21}$J, equivalent to 1.6 $\times 10^{11}$t of standard coal.

In general, with the continuous progress of science and technology and the improvement of research methods, researchers can collect more accurate data, and the research accuracy of geothermal field and thermal history in the surrounding areas of the Bohai Sea has been significantly improved, and the research scope has also been expanded, as shown in Table 1.

Table 1: Statistical table of geothermal gradient calculation in different periods

Chen Moxiang 1984 (Ground temperature gradient °C / 100m)	Qiu Nansheng 2009 (Ground temperature gradient °C / 100m)	Gong Childbearing Age 2016 (Ground temperature gradient °C / 100m)
Qikou sag: 3.0-3.3	JiZhong sag:2.82-3.66	Jizhong sag:2.08-4.10
Haizhong Rise: 3.7-5.0	Jiyang sag:3.11-4.09	
Bozhong sag:3.0-3.2	Huangye sag:3.14-3.60	
Bodong sag:3.2-3.5	Lingqin sag:2.86-3.36	
Jiaoliao rise:3.5-5.0	Liaohe sag:3.12-3.82	

2.2 Research Status of Geothermal Energy in the Yellow Sea

The Yellow Sea is the largest marginal sea in the western Pacific Ocean between China and the Korean Peninsula. It has the narrowest sea surface from the Chengshanjiao of Jiaodong Peninsula to the long mountain string of North Korea. It is customary to divide the Yellow Sea into two parts: the North Yellow Sea and the South Yellow Sea. The area of the North Yellow Sea is about 81,000 square kilometers, and the area of the South Yellow Sea is about 409,000 square kilometers. However, compared with the terrestrial heat flow studies of the East China Sea shelf, the Bohai Bay Basin, the Yinggehai Basin, etc., the public heat flow data are extremely scarce, and the area of the North Yellow Sea is smaller than that of the South Yellow Sea.Therefore, no relevant geothermal research has been carried out. Yang Shuchun et al. [8] used the existing drilling temperature measurement data and the determination of thermal conductivity of rock samples in the southern basin of the South Yellow Sea to compile a geothermal trend map. The results show that the current geothermal gradient in the southern basin of the Yellow Sea is between 24.7-32 ℃ / km, and the terrestrial heat flow is between 65-74mW / m^2.Its plane distribution shows a trend of high in the north and low in the south, and high in the west and low in the east. Guo Xingwei et al. [9] through the analysis of terrestrial heat flow value, it is concluded that the heat flow of the South Yellow Sea is at a low level on the continental margin of East Asia, reflecting the relatively cold geological background of the South Yellow Sea on the continental margin of East Asia. The research results of Sun Xudong [10] show that the formation heat generation rate in the South Yellow Sea area increases with the increase of age.

In general, the research investment in the Yellow Sea region is insufficient, resulting in extremely scarce geothermal data. The study of geothermal field characteristics and thermal history in the South Yellow Sea region is of great significance for evaluating the potential of oil and gas resources and geothermal resources in the region, as well as understanding the basin structure and thermal evolution process.

2.3 Research Status of Geothermal Energy in the East China Sea

The East China Sea region, located at the junction of the Eurasian plate, the Pacific plate, and the Philippine plate, plays an important role in the Western Pacific. It is an important part of the Cenozoic trench and arc-basin system [11].

Bi Chuanxue et al. [12] preliminarily analyzed the heat flow distribution and its geological significance in the East China Sea. The weighted average of geothermal gradient in the East China Sea is 36.6 °C / km, and its plane distribution is characterized by high in the east and low in the west, high in the south and low in the north. Xu Weiling et al. [13] calculated the corresponding geothermal gradient by collecting data from 8 wells, and concluded that the East China Sea shelf area is generally presented as a large and wide thermal uplift. The highest part of the uplift is in the eastern part of the shelf basin, that is, under the deep depression with the largest Cenozoic sedimentary thickness. TONG Zhigang et al. [14] extrapolated the drilling geothermal research results to the well-free area by using the correlation between geothermal temperature and formation depth or the depth of the lower boundary of the lithosphere, established the regional geothermal field of Xihu sag in the East China Sea, and analyzed its effect on source rocks. The results show that the average geothermal gradient in the northern and southern parts of the depression is higher, and the central part of the depression is relatively low. The thermal evolution degree of source rocks in Pinghu Formation is higher in the north than in the south. Yu Zhongkun et al. [15] also used the method of extrapolating the drilling geothermal research results to the well-free area to systematically establish the regional geothermal field of Lishui Sag for the first time and analyze its effect on the evolution of hydrocarbon source rocks. The results show that the ground temperature difference between each exploration well can reach 40 °C. The average geothermal gradient ranges from 26 °C / km to 37 °C / km. It is concluded that the geothermal gradient at the edge of the depression is higher and the geothermal gradient in the middle of the depression is lower.

At present, the geothermal research in the East China Sea is mainly based on the existing drilling geothermal research results to extrapolate to the well-free area, and to establish the regional geothermal field in different regions. In the follow-up research process, it is necessary to increase the collection of ground temperature data in the region, and verify whether the previous theory is established. The existing conclusions can also play an important role in the follow-up research.

2.4 Research Status of Geothermal Energy in the South China Sea

The South China Sea is located at the intersection of the Eurasian plate, the Indian-Australian plate and the Pacific-Philippine sea plate. It is one of the largest marginal seas in the western Pacific and has a complex tectonic evolution history. (Li Jiabiao, tectonic evolution model of Cenozoic seafloor spreading in the South China Sea: new insights from high-resolution geophysical data)

In the late 1990 s, He Lijuan et al. [16] first counted and analyzed 584 heat flow data in the South China Sea area, and described the distribution characteristics of heat flow in the South China Sea, and pointed out that the South China Sea area as a whole is characterized by high heat flow. Among them, the average heat flow value of the central basin is the highest (90 mW / m2), while the average heat flow value of the eastern margin of the basin is the lowest (55 mW / m2), and the heat flow values of the other edges of the basin are basically close. Shi Xiaobin et al. [17] collected 592 heat flow data in the South China Sea and carried out systematic analysis to study the distribution characteristics of the heat flow in the South China Sea on the plane. These heat flow data are mainly distributed in the southern and northern continental margins of the South China Sea, and a few are distributed in the eastern continental margin and sea basin of the South China Sea, while there are fewer heat flow data in the western continental margin of the South China Sea, Xisha-Zhongsha Islands and Nansha Block. The areas with extensional background, such as the northern continental margin, the Mekong Basin and the northern Palawan Basin, have medium-high heat flow. The heat flow in the trench area is relatively low, and the eastern trench area is a low heat flow area except for the southwestern Taiwan Basin, China, while the ancient trench area in the eastern part of the southern margin is in thermal recovery. The western area of the southern edge has high heat flow due to the torsion of the boundary fault and the abnormal supply of the deep heat source. The western margin of the shear fault zone also has high heat flow characteristics; the heat flow in the Zhongsha-Xisha area is moderately high and increases from NW to SE, while the heat flow in the Nansha area is low, about 60 mW / m2. The heat flow in the basin basically meets the law of decreasing with the increase of oceanic crust age. The measured heat flow in the eastern sub-basin is basically consistent with the theoretical prediction, while the measured heat flow in the southwestern sub-basin is generally lower than the predicted value. A high heat flow zone is identified in the lower continental slope of the northern South China Sea, which is basically consistent with the location of the fault zone in the northern margin of the basin. Yuan Yusong et al. [18] noted that the geothermal gradient is closely related to the calculation depth, and proposed to use ' normalization ' to calculate the geothermal gradient of the Pearl River Mouth Basin and the Qiongdongnan Basin, and more accurately evaluate the current geothermal state of the two basins. Zhang Jian et al. (Zhang Jian, deep geothermal characteristics of the northern continental margin of the South China Sea) and Shan Jingnan et al. [19-20] calculated the thermal structure and deep temperature of the northern continental margin of the South China Sea. The calculation results show that although the heat flow background in this area is very high, the proportion of crustal heat flow in the surface heat flow is not more than 35 %, and the proportion decreases gradually from the northern continental margin to the southern central basin. The thermal structure of each basin in the calculation area is also heterogeneous. The inhomogeneity of the thermal structure of the basins in this area is related to the factors such as the thinning of the continental shelf crust and the upwelling of the asthenosphere. The temperature range of the Moho surface basically fluctuates around 600 ℃, and the maximum temperature can reach 726 ℃.

In general, the current geothermal field research in the South China Sea is mainly concentrated on the northern continental margin. The geothermal characteristics and deep thermal state of the South China Sea are directly or indirectly controlled by its tectonic environment. The northern continental margin basin belongs to the 'cold crust hot mantle 'type basin.

3. Summarization of the Status Quo of China's Marine Research

China has a vast sea area, including rich marine thermal energy resources. The development of marine geothermal energy is mainly carried out by means of submarine heat pump and seawater bath thermal energy utilization. At present, some marine energy pilot projects have been carried out, laying a foundation for the long-term development of marine geothermal. However, since the 1980 s, there has been insufficient research on the four major sea areas of China, as shown in table 2 below. Geothermal data in China are abundant, and four systematic compilations have been carried out. However, there are few reports on geothermal data in China's oceans and their basins, and they have not been systematically collated. Based on the newly added drilling temperature data in recent years, Tang Xiaoyin [21] added 810 geothermal gradient data in the study area, and collected geothermal data from domestic and foreign databases and journals. On this basis, the geothermal gradient data and geothermal heat flow data of the basins in the China Sea and adjacent areas were systematically sorted out for the first time (Table 3), and its contour map (Figure 2) was drawn. The results show that the average geothermal gradient in the China Sea and its adjacent basins is 43.2 ±

25.7 ℃ / km, and the average terrestrial heat flow is 74.4 ± 26.6 mW / m^2. The average terrestrial heat flow in most basins is higher than 65 mW / m^2, which belongs to the 'hot basin '. The present-day ground temperature distribution in the China Sea and its adjacent basins shows obvious ' two-zone ', that is, the ground temperature in the nearshore zone is low, and the ground temperature in the farshore zone is high. In the basin group in the eastern sea area, the overall ground temperature distribution shows the characteristics of ' high in southeast and low in northwest'.

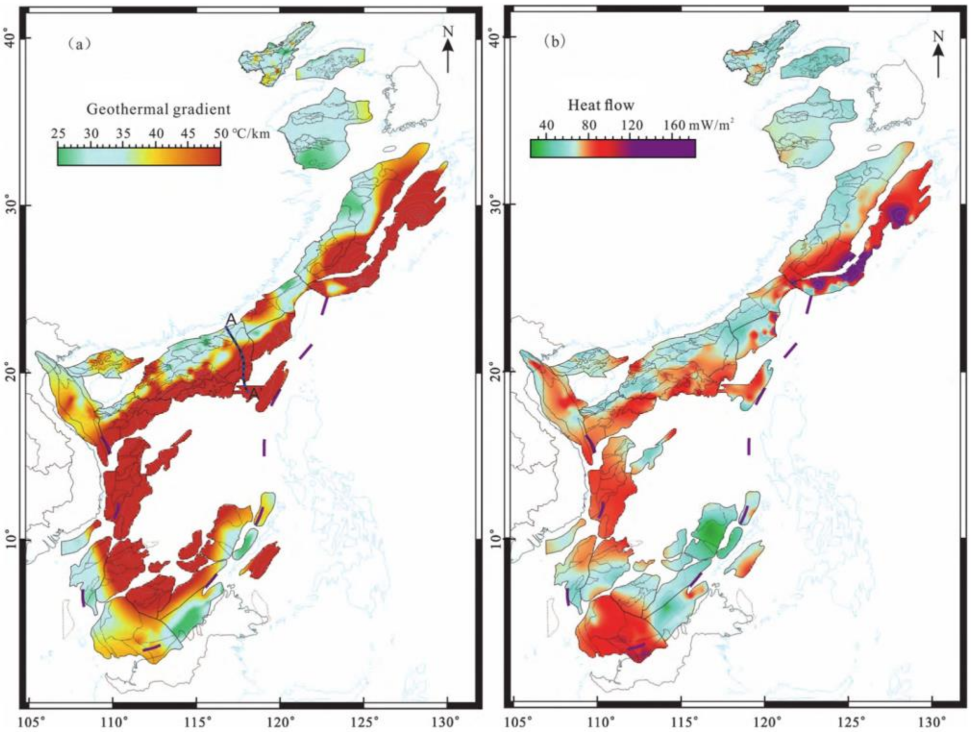
Table 2: Comparison of heat flow research in four major sea areas in China (according to Sun, 2020)

sea area	Character (Time)	High-quality heat flow data	proportion	remark	heat flow (mW / m^2)
bohai sea	Qiu Nansheng et al. (2009)	112	7.89%	From drilling	64
yellow sea	Yang Shuchun et al. (2003)	8	0.56%	There are only 8 drilling data.	69
east china sea	Xu Weiling et al. (1995)	300	21.13%	Most of them are from the Okinawa Trough, and there are only 26 drilling geothermal data on the shelf.	71
the south china sea	Yuan et al.(2009) Mi Lijun et al. (2009)	1000	70.42%	It has drilling heat flow data and probe heat flow data.	

Table 3: Statistical table of terrestrial heat flow and geothermal gradient in the main basins of China Sea and its adjacent areas

basin	heat flow			geothermal gradient		
	mean value (mW/m^2)	range (mW/m^2)	Number (units)	mean value (°C/km)	range (°C/km)	Number (units)
bohai sea	64.6±7.4	50~82	97	32.9±8.8	15.1~64.2	619
south yellow sea	67.3±3.4	61~74	10	28.5±2.5	24.7~32.0	8
east china sea shelf	68.1±8.2	50~88	43	33.0±5.7	22.5~49.1	47
zhujiang river estuary	75.3±18.4	40~163	257	52.6±30.4	21.1~192.0	359
north bay	67.8±10.2	42~88	40	38.2±9.0	18.0~57.2	112
yingge sea	74.9±18.4	35~119	69	42.8±6.3	31.7~69.9	55
southeast hainan	72.3±14.7	42~112	73	49.3±22.9	26.3~120.4	78
Zeng Mu	94.1±15.2	64~125	26	39.5±4.5	30.0~49.0	20

In general, there are some progress in the study of marine geothermal energy, but there are also many shortcomings and areas that have not yet been carried out, such as the lack of research on the characteristics and causes of the current geothermal field in a certain sea area, and the lack of economic evaluation of marine geothermal energy development and utilization.



A—A’—one geoscience section across northern South China Sea (after Yao Bochu, 1998)

Figure 2: Contour maps of geothermal gradient (a) and heat flow (b) for basins in China's offshore and adjacent areas

4. Future outlook

Prospects for the future of marine geothermal development and utilization:

1) The collection of seafloor heat flow data is insufficient. In addition to the South China Sea, the borehole heat flow data in other sea areas are scarce. The complex marine environment and harsh seabed geological conditions make the development technology of marine geothermal energy face certain challenges. Submarine drilling, heat exchange system design and maintenance need to overcome technical problems.

2) Compared with terrestrial geothermal, the development cost of marine geothermal is higher. The marine environment requires the use of special equipment and technology, increasing investment and operating costs, which may pose a certain obstacle to the economic feasibility of marine geothermal.

3) Marine geothermal development may produce certain environmental impact. For example, the drilling process may lead to geological changes in the seabed and have a certain impact on the ecosystem and marine biodiversity. Therefore, careful planning and management are needed to protect the marine ecological environment.

4) Compared with the development experience of terrestrial geothermal energy, marine geothermal energy is relatively less in technology and engineering practice. The lack of large-scale demonstration projects and related operational management experience has limited the pace of marine geothermal development.

In view of the research status of marine geothermal energy in the four major sea areas along the coast of China, in the future, we can conduct a more comprehensive survey from two aspects: geological survey and geothermal resource survey. The geological survey section needs to more clearly identify the geological characteristics of the sea area, including crustal structure, underground heat flow, etc., to help us better understand the distribution and formation mechanism of marine geothermal energy. The general situation of geothermal resources requires a detailed understanding of the geothermal resources in different sea areas, including the distribution, temperature and availability of resources such as submarine hot springs, hydrothermal channels and underground hot rocks.

In addition to summarizing the current situation, we can also look forward to the future development trend of marine geothermal energy. With the progress of science and technology and the growth of energy demand, marine geothermal energy is expected to play a greater role. Future research and development should focus on improving development efficiency and technology maturity, reducing costs, and strengthening environmental protection measures. In terms of application fields, marine geothermal energy can be used in heating, power generation, marine agriculture and other fields to contribute to energy transformation and sustainable development. However, the development of marine geothermal energy still faces some challenges, including technical problems, economic feasibility and environmental impact. Strengthening research cooperation, providing policy support and cooperating with other forms of clean energy will help to promote the development of marine geothermal energy.

5. Conclusions

In short, marine geothermal energy, as a potential and important form of energy, is of great significance for solving energy shortages and reducing environmental pollution. Through in-depth research, technological innovation and policy support, we can make full use of the potential of marine geothermal energy to promote the transformation of clean energy and the sustainable development of future energy supply.

References

[1] Cao Rui, Duo Ji, Li Yubin, etc. The occurrence characteristics, development status and prospect of medium-deep geothermal resources in China. Journal of Engineering Science, 2022, 44 (10): 1623-1631.DOI: 10.13374 / j.issn2095-9389.2022.04.07.003.

[2] Lin Wenjing, Liu Zhiming, Wang Wanli, etc. Geothermal Resources and Their Potential Assessment in China. China Geology, 2013, 40 (01): 312-321.

[3] Han Dong, Wang Ruoxuan. Characteristics and reserves evaluation of geothermal resources in Bohai Sea. Energy and energy conservation, 2023, (10): 67-70.DOI: 10.16643 / j.cnki.14-1360 / td.2023.10.01.

[4] Chen Moxiang, Huang Geshan, Wang Jian and so on. Preliminary study on the characteristics of geothermal field in Bohai Sea.Geology, 1984, (04): 392-401.

[5] Hu Shengbiao, Zhang Rongyan, Luo Yuhui, etc. Thermal history and oil and gas resource potential of Bohai Sea Basin.Oil and gas in China offshore. Geology, 2000, (05): 13-21.

[6] Gong Yuling, Wang Liangshu, Liu Shaowen and so on. The distribution characteristics of terrestrial heat flow in the Jiyang depression. China Science (Series D: Earth Science), 2003, (04): 384-391.

[7] Qiu Nansheng, Wei Gang, Li Cuicui, etc. Distribution Characteristics of Present Geothermal Field in Bohai Sea. Petroleum and Gas Geology, 2009, 30 (04): 412-419.

[8] Yang Shuchun, Hu Shengbiao, Cai Dongsheng, etc. Geothermal field characteristics and thermal-structural evolution of the southern basin of the South Yellow Sea.Scientific Report, 2003, (14): 1564-1569.

[9] Guo Xingwei, Sun Xudong, Yang Xiaoqiu and so on. A new terrestrial heat flow value in the central uplift of the South Yellow Sea: heat flow measurement results of Well CSDP-2.According to Geophysical Journal, 2023,66 (01): 332-343.

[10] Sun Xudong. Analysis of terrestrial heat flow, formation heat generation rate and thermal structure in the South Yellow Sea. China University of Geosciences (Beijing), 2020.DOI: 10.27493 / d.cnki.gzdzy.2020.00066.

[11] Guo Lingzhi, Shi Yangshen. The formation and evolution of Mesozoic and Cenozoic active continental margins and island arc structures in the Western Pacific. ACTA GEOLOGICA SINICA, 1983, (01): 11-21.DOI: 10.19762 / j.cnki.dizhixuebao.1983.01.002.

[12] Bi Chuanxue, Yang Ling, Wu Guohua, etc. Characteristics of heat flow in the East China Sea and its geological significance. Jiangsu Geology, 1994, (01): 30-36.
[13] Xu Weiling, Jiao Rongchang, Le Junying and so on. Geothermal studies on the continental shelf of the East China Sea.Progress in geophysics, 1995, (02): 32-38.
[14] Tong Zhigang, He Qing, He Shibin et al. Geothermal field and its effect on source rocks in Xihu Sag, East China Sea.Petroleum Experimental Geology, 2009,31 (05): 466-471 + 484.
[15] Yu Zhongkun, Zhao Hong, Diao Hui et al. Thermal evolution simulation and current geothermal field characteristics of Lishui Sag in the East China Sea Shelf Basin. Marine Geology and Quaternary Geology, 2020,40 (02): 124-134.DOI: 10.16562 / j.cnki.0256-1492.2019061402.
[16] He Lijuan, Xiong Liangping, Wang Jiyang. Geothermal Characteristics of the South China Sea Basin. Offshore Oil and Gas in China. Geology, 1998, (02): 15-18.
[17] Shi Xiaobin, Qiu Xuelin, Xia Kanyuan, etc. Characteristics of heat flow in the South China Sea and its tectonic significance. Journal of Tropical Oceanography, 2003, (02): 63-73.
[18] Yuan Yusong, Zheng Herong, Zhang Gongcheng, etc. Cenozoic thermal evolution history of the deep-water area in the northern South China Sea. Geology, 2009, 44 (03): 911-921.
[19] Zhang Jian, Wang Jiyang. Deep geothermal characteristics of the northern continental margin of the South China Sea.Scientific Report, 2000, (10): 1095-1100.
[20] Shan Jingfu, Zhang Gongcheng, Wu Jingfu, etc. Thermal structure and Moho temperature in Qiongdongnan Basin, northern margin of the South China Sea. Geophysical Journal, 2011, 54 (08): 2102-2109.
[21] Tang Xiaoyin, Zhong Chang, Yang Shuchun and so on. Characteristics of present geothermal field and its influencing factors in basins of China Sea and adjacent areas. Geological Journal, 2023,97 (03): 911-921.DOI: 10.19762 / j.cnki.dizhixuebao.2022087.