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The Millennium Mystery of "Boiling Wells" and Evidence from Geoscience: The Case of Jiuli Village

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Abstract: *The six ancient wells and the geological environment around Jiuli Village of Danyang City in Jiangsu Province have been explored in detail through the application of inorganic and organic chemical analysis, controlled source audio-frequency magnetotellurics, high-density resistivity, radon gas measurements and other geochemical and geophysical methods. The six wells are 30-200 centimeters apart from each other and have been boiling for more than 2000 years. This study finds that: (1)* CO_2 *is the main boiling gas in the "boiling wells", and there are also traces of radon gas and total volatile organic compounds (TVOC), which are not detected in the nearby non-boiling wells. (2) The contents of free carbon dioxide, calcium iron, manganese, total dissolved solids, total hardness, bicarbonate and rare earth elements in water samples from "boiling wells" are significantly higher than those taken from other civil wells and lakes around the "boiling wells". (3) The water temperature of the "boiling wells" (about 19 ºC in summer) is basically the same as that of other surrounding civil wells, and no abnormal situation is observed. (4) There are basalt rock mass and the secondary fault of Maodong fault in the deep underground of the "boiling wells". The radon gas content in the exposed areas of these faults is obviously higher than that observed in other places. (5) The existence of "boiling wells" is closely related to the Maodong active fault. The boiling gas in the "boiling wells" mainly comes from the deep crust or upper mantle, and the gas can rise along the fault zone and escape from the surface. (6) The water tastes of the six "boiling wells" are different because of the different contents of free carbon dioxide, calcium iron, manganese and pH values of water in "boiling wells". The "three limpid and three turbidity" of the "boiling wells" water is mainly related to the iron contents in well water. The main reason for the turbidity of well water is that the well water with high iron content can be oxidized to the precipitation of ferric iron through exposure to air.*
Key words: *ancient well; "boiling wells"; Jiuli village; Maodong fault; Millennium MysterY*

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I. Introduction

Jiuli Village, which is located near to Yanling Town of Danyang City in China's Jiangsu Province, is famous for the Jizi temple. Around 100 meters southeast of Jizi temple there are six ancient wells, which are distributed across an area of about 10 square meters (Fig. 1). These wells are almost distributed along a north-south direction and are less than two meters apart from each other, and the nearest interval is only 30 or 40 centimeters. The depth of the wells is about 3-4 meters, and the temperature of the well water during summer is about 19 ºC. The well water in these six ancient wells boils all year, just like a boiling pot, and these wells are therefore known as "boiling wells". More strangely, the well water of these six wells is "three limpid and three turbidity" and tastes different. The three wells in the north are limpid-water wells (which taste of beer, lemon and Sprite), and the three wells in the south are turbidity-water wells (which taste of rust, bitterness and piquancy). According to historical records, the history of the "boiling wells" stretches back more than 2000 years, and they originally became an important part of the landscape of Jizi temple during the early century of Southern Dynasty. At that time, there were more than 100 wells, some of which were "boiling wells". Historical changes resulted in most of the "boiling wells" being buried. In 2001, the Jizi temple scenic area in Danyang began to be renovated on a large scale, and six "boiling wells" were found and cleaned up, one after the other. These "boiling wells" are not Spring spots, and their characteristics and causes of formation are totally different from those of Spouting Spring in Jinan, Pearl Spring in Nanjing and so on. Subsequent to consulting relevant domestic and international literatures, the authors did not find a report that engaged the same geological phenomena as that evidenced in Jiuli Village.

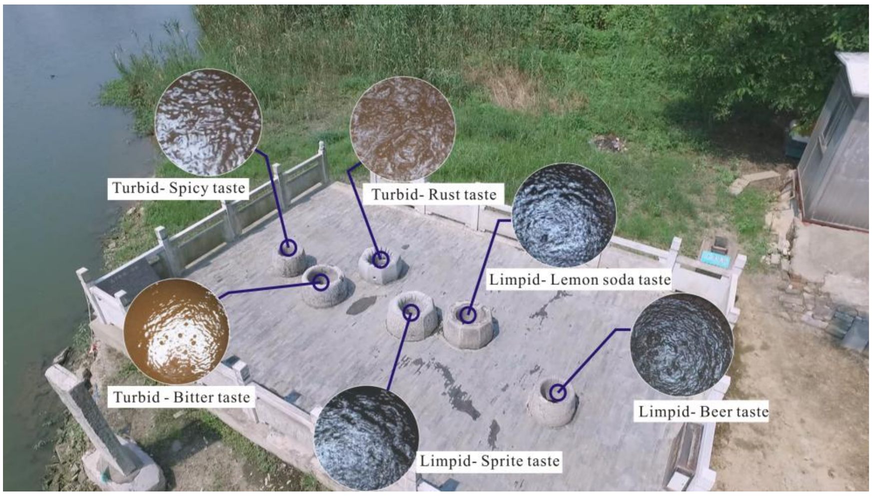

Fig. 1 Location map of 6 "Boiling wells" in Jiuli village, Yanling town, Danyang city, Jiangsu province

The "boiling" phenomenon of the well water in these six ancient wells, the causes of the limpidity and turbidity of well water and the reasons for different tastes have not been resolved so far, and have indeed been mysteries for thousands of years. Upon seeing the gas boiling out of the well water, local villagers speak of a "dragon gas" that is exhaled by an underground dragon. Some geographers and tourists offer a more prosaic explanation when they claim that chemical and physical processes form biogas, CO_2 and other gases in local marshes. It has also been claimed that the gas may originate from deep underground. These claims have escaped confirmation, and there is still a geological mystery to be resolved. Accordingly, the purpose of this study is to identify the composition of boiling gas and underground water in "boiling wells" and to further explain the geological origin and formation mechanism of "boiling wells" upon a scientific basis. This will be achieved by engaging with the structural geological conditions in the "boiling wells" area.

1. Geological background

The "boiling wells" in the Danyang area of Jiangsu Province are distributed within the "Maodong fault zone" on the east side of Mao Mountains (Fig. 2). Drilling data shows that the lower stratum is Cretaceous siltstone, sandstone and mudstone, and the upper stratum is Paleogene and Quaternary loose sediments, which are mainly silty clay with silt and sand. In addition, a set of Paleozoic-Mesozoic sedimentary strata have also emerged in the Mao Mountains area, which is to the west of the wells. The "boiling wells" are excavated in the Quaternary surface stratum, and they contain phreatic water.

Maodong fault is located in the foothills of Mao Mountain. It is intermittently exposed, and it twists and turns as it extends in a north to northeast direction. It passes through the Ningzhen Mountains and the Yangtze River as it extends towards Xinghua in northern Jiangsu Province[1-4]. It has a total length of more than 300 kilometers, and the nearly east-west fault of Qingyang-Ningguo in Anhui Province cuts across it as it extends in a southerly direction. When observers look on from Gaochunhua Mountain, Lishuizhi Mountain and the Zhuhuang Coal Mines in Liyang, they can see that the Cretaceous Pukou Formation, the lower Triassic limestone and the Permian Longtan Formation evidence the characteristic of fault contact.

The Bouguer gravity anomaly diagram establishes that the research area is located at the boundary between high and low gravity value areas, with high gravity being evidenced in Jurong City in the west and low gravity being evidenced in eastern Shangpeibu Town in the east (Fig. 3). The results of the aeromagnetic survey establish that the research area is located in the anomaly belt of Mao Mountains (Fig. 4): the western side is a disordered magnetic anomaly zone that reflects the distribution of volcanic rocks, while the eastern side is a positive magnetic anomaly zone that is related to the red bed (upper Cretaceous series - paleogene system).

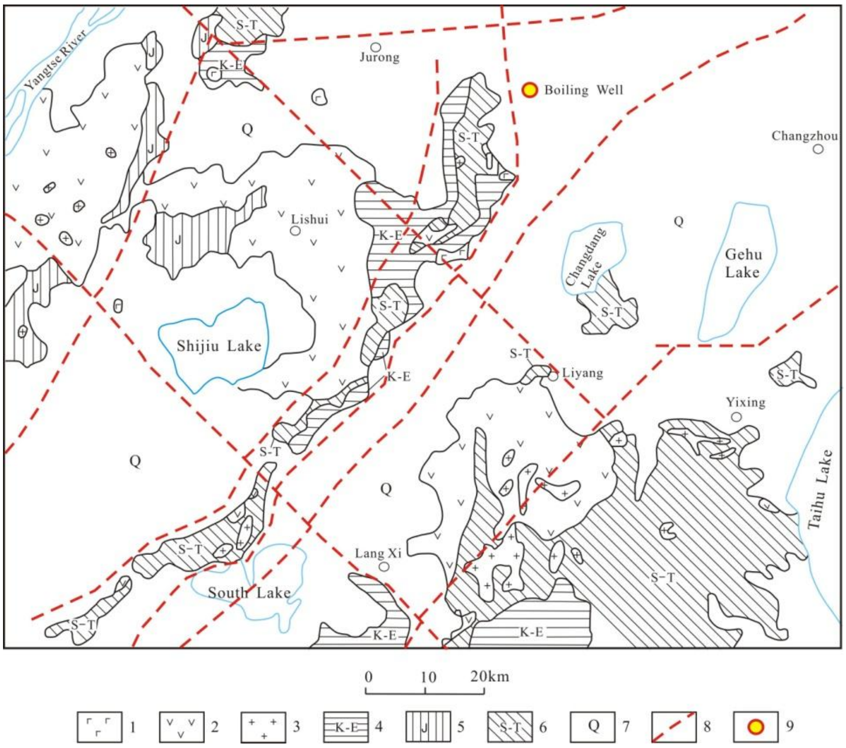

Fig.2 Geological map of the " Boiling wells " in Danyang City, Jiangsu Province and its surrounding area

1. Cenozoic volcanic rocks. 2. Mesozoic volcanic rocks. 3. Intermediate-acidic intrusive rocks. 4. Red layer of Mesozoic era. 5. Xiangshan group. 6. Gaojiabian-fanjiatang group. 7. Quaternary. 8. Fault. 9. Boiling well

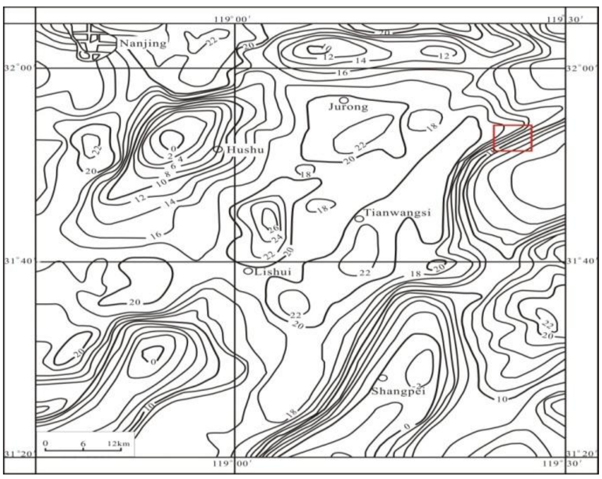

Fig.3 The map of Bouguer gravity anomaly in Lishui area (red frame is the research area)

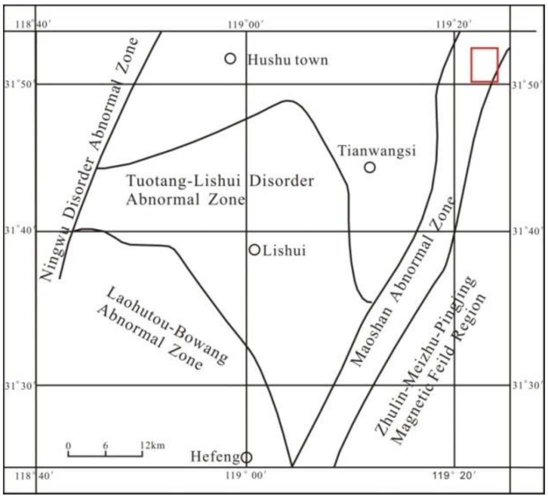

Fig.4 Sketch of aeromagnetic anomaly zoning in Lishui area (red frame is the research area)

From the beginning of the Middle Pleistocene, it is known that the remobilization of Maodong fault results in the continuous uplift of the Mao Mountains in the west: similarly, the Zhixi depression in the east shows a continuous decline, receiving the loose sediments of the Tertiary and Quaternary with a thickness of nearly one kilometer. The Zhixiqiao-Yaxigang depression on the eastern side of Mao Mountains is still sinking at a speed of about 1.25 mm/yr [5]. The seismic data suggests that destructive earthquakes have occurred many times along the fault zones, including those in Lishui, Liyang, Yangzhou and Zhenjiang. Microseisms also clearly present the characteristic of zonal distribution (Table 1, Fig. 5).

Table 1 The middle-strong earthquakes in Maodong fault zone

	Seismogenic time			Epicentral position			Earthquake magnitude (Ms)
	Year	Month	Day	East longitude	North latitude	Site	
1	1624	02	10	119°24′	32°24′	Jiangsu Yangzhou	6
2	1676	06	11	119°24′	32°24′	Jiangsu Yangzhou	4.75
3	1679	12	26	119°30′	32°24′	Jiangsu Liyang	5.25
4	1748	06	30	118°24′	30°42′	Anhui Jingxian	5
5	1839	10	12	119°12′	31°30′	Jiangsu Liyang	4.75
6	1872	07	24	119°18′	32°12′	Jiangsu Zhengjiang	4.75
7	1913	04	3	119°24′	32°12′	Jiangsu Zhengjiang	5.5
8	1930	01	3	119°24′	32°12′	Jiangsu Zhengjiang	5
9	1974	04	22	119°19′	31°28′	Jiangsu Liyang	5.5
10	1979	07	9	119°15′	31°27′	Jiangsu Liyang	6
11	2012	07	20	119°36′	33°00′	Jiangsu Gaoyou	4.7

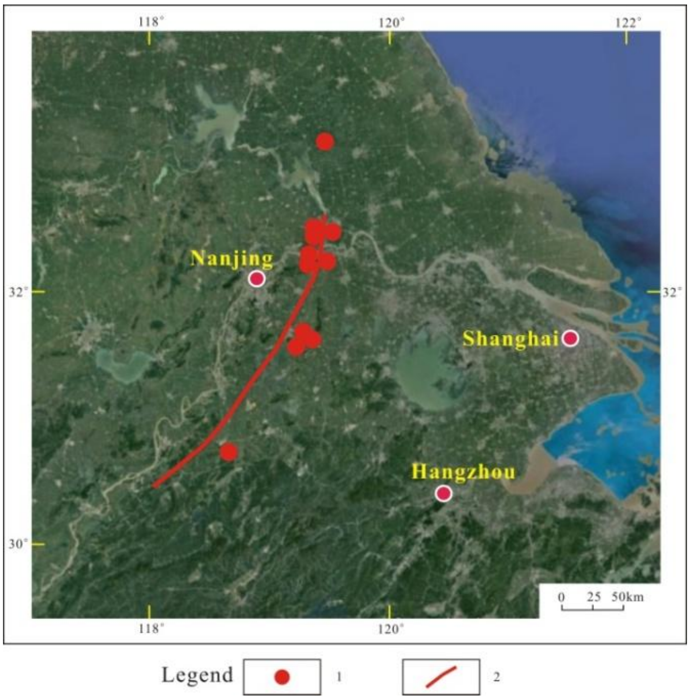

Fig.5 Sketch of the distribution of the middle-strong earthquakes in Maodong fault zone in Maodong fault zone

1. the earthquake point; 2. fault

Drilling tests reveal that the cross-section of Maodong fault is steep and sometimes reverses to form a sharp curve bend. In addition, once the combination relationships between this fault and a series of thrust faults and reversed folds arranged in en echelon mode in Mao Mountains are analyzed, it becomes apparent that the fault has a strong left-lateral translation property. Geophysical prospecting infers that the fault cuts deep into the upper crust. The fault is therefore a compressive normal fault (early tension and late compression) that has left-lateral translation characteristics, which was active in the Yansha period-Himalayan period. In the northern section of the Mao Mountains, the fault zone is composed of a group of faults.

II. Research methods

In addition, to fully collecting and utilizing data from previous aeromagnetic, drilling, gravity and regional geological surveys, along with data extracted from other sources, the authors also carried out geological geochemical and geophysical exploration of the "boiling wells" and their surrounding geological environment –

this included chemical analysis, controlled source audio-frequency magnetotellurics (CSAMT), high-density resistivity and radon gas measurements of the well water in "boiling wells" in addition to other wells and the lake water around them. This established a basis for the comprehensive study and analysis of the formation mechanism of "boiling wells". The East China Mineral Resources Supervision and Detection Center, which is within the Ministry of Land and Resources, undertook chemical analysis of water samples. The inorganic chemical components were mainly tested by inductively coupled plasma spectrometer, atomic fluorescence spectrometer, ion chromatography, ultraviolet spectrophotometer and other instruments. The Nanjing geological survey center of China Geological Survey undertook measurements of high-density resistivity, radon gas and total volatile organic compounds (TVOC). TVOC was tested through the application of a PhoCheck Tiger portable VOC gas detector made in Britain, while Radon gas was measured through a RAD7 radon gas detector made by Durridge Company, who are based in the US. The high-density resistivity meter was a domestic DUK-2 high-density electrical measurement system. The Institute of Resource Geophysics from within the Geological Exploration Technology Institute of Jiangsu Province was responsible for CSAMT exploration, and the V8 electrical system that is produced by Canada Phoenix Geophysics Co. Ltd was applied.

III. Research results

3.1 Maodong fault zone and its characteristics revealed by magnetotelluric sounding results

The authors have measured four CSAMT profiles along Maodong fault zone and "boiling wells" (Fig. 6), and find obvious changes from low resistance to high resistance on both sides of Mao Mountains. At both Maoxi Fault (F1) and Maodong Fault (F2) it is also possible to clearly identify a north-north-east trend. (Fig. 7)

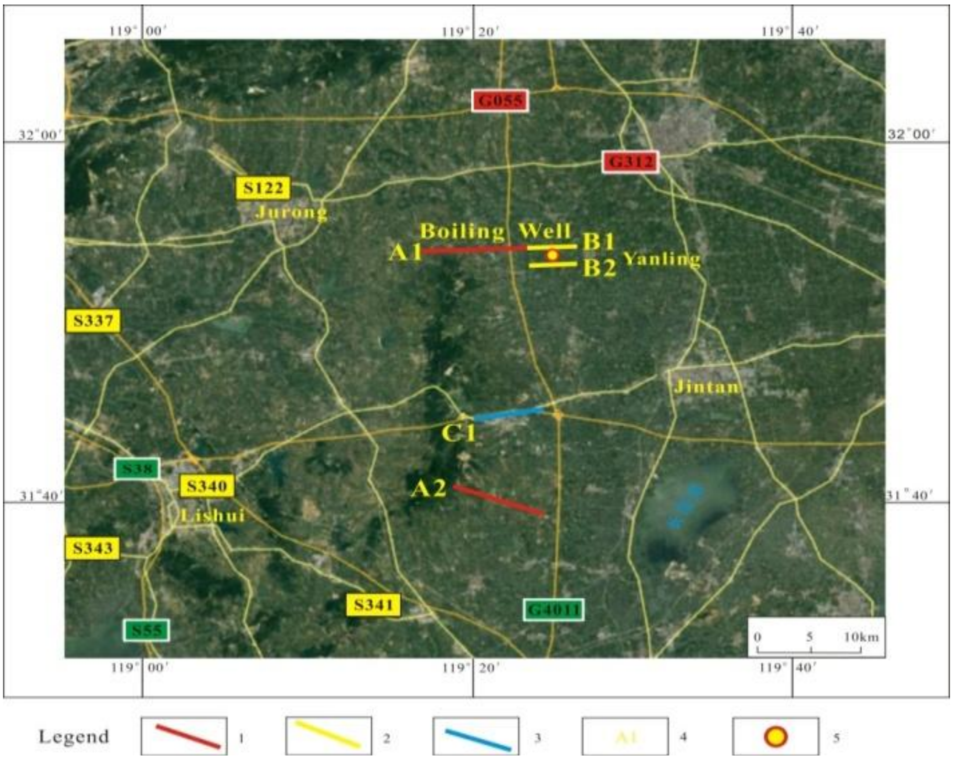

Fig.6 Sketch of the controlled source audio magnetotelluric (CSAMT) survey lines in Maodong fault zone

1. CSAMT exploration line completed in 2014; 2. CSAMT exploration line completed in 2013; 3. The CSAMT survey line has been collected; 4. CSAMT exploration line number; 5. Location of boiling wells

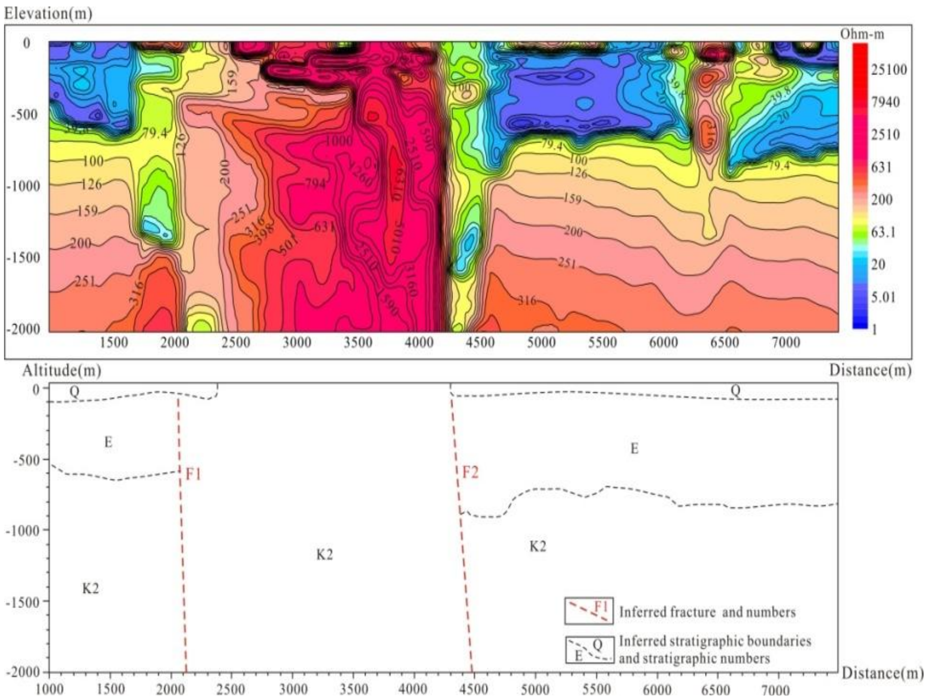

Fig.7 Sketch of controlled source audio magnetotelluric profiles (A1) and geological inferences （The section position is shown in figure 6） in Maodong fault zone

1. Inferred stratigraphic boundary and stratigraphic number; 2. Inferred fault structure and number

The "boiling wells" are about 6 km away from Maodong's main fault. CSAMT profiles across the "boiling wells" show that there are secondary faults (F11 and F12) in the Jiuli village area's Maodong fault (Fig. 8), which distribute in the northeast trend. Jiuli village is situated in the basin along the northwest direction of Zhixiqiao depression, and the upper part covers the Paleogene (E) and Quaternary (Q) strata and evidences a relatively large thickness (about 800~1000 m); the lower part (about 1000~1200 m) is the Upper Cretaceous (K2) stratum. Figure Eight shows that the top boundary of the Upper Cretaceous (K2) in the Zhixiqiao fault depression shifts from shallow to deep as it extends from northwest to southeast. In the Paleogene (E) stratum, there are obvious high resistivity anomalies at the elevation of -400~-600 m below the two measuring lines, and the apparent resistivity value is greater than 40 Ω·m. Reference to the drilling and physical data of Yanling 743 hole establishes that the resistivity and density of basalt in Paleogene (E) are clearly higher than other lithologies. The local high resistivity anomaly also shows high value characteristics in 1:50000 residual gravity anomaly and the local high value anomaly in 1:50000 aeromagnetic. It can be inferred that the high resistivity body may be the basalt (βν) in Paleogene (E).

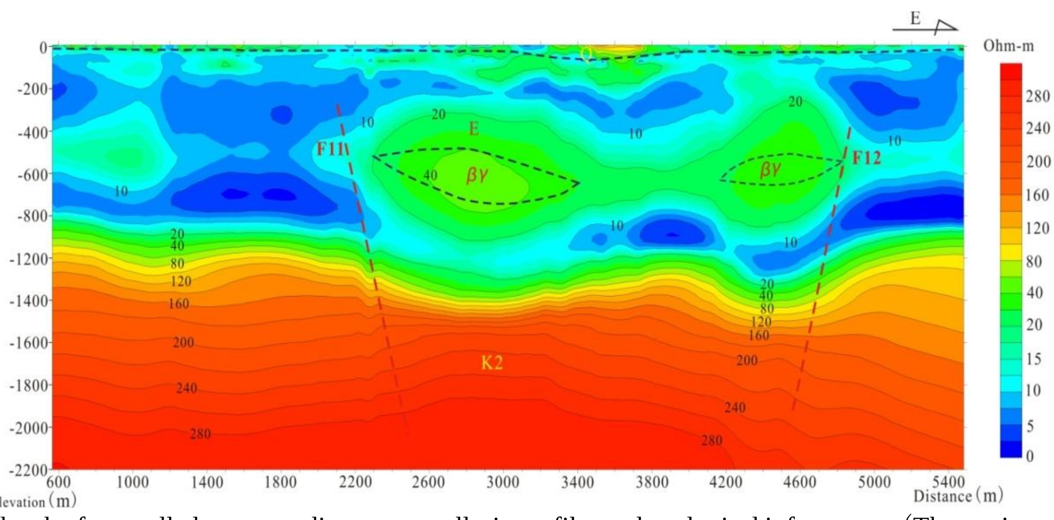

Fig.8 Sketch of controlled source audio magnetotelluric profiles and geological inferences （The section position is shown in figure 6） across "Boiling wells" in Danyang City, Jiangsu Province

3.2 The water quality of "boiling wells" is different from that of other civil wells and lakes around.

In order to compare the difference between water from "boiling wells" and water taken from other wells and lakes around, water samples were collected respectively. Chemical analysis revealed that the contents (free carbon dioxide, bicarbonate ion, calcium ion, total soluble solids, total hardness, iron, manganese, light rare earth and other chemical components) of water taken from "boiling wells" are significantly higher than water taken from civil wells and lakes (Table 2). For example, the content of free carbon dioxide in water taken from "boiling wells" ranges from 439 mg/L to 491 mg/L, while water taken from civil wells and lakes contains less than 4 mg/L. The content of bicarbonate ion in water taken from "boiling wells" ranges from 618 mg/L to 1289 mg/L, while water taken from civil wells contains less than 156 mg/L. Of these chemical components, the contents of iron, manganese, total dissolved solids and total hardness exceed the grade Ⅲ water quality set out in the Quality standard for ground water (GB/T14848-2007). In addition, chloroform and dichloromethane can be detected in water taken from the civil wells and lakes, and this appears to have been caused by pollution resulting from economic activities. Most tests demonstrate that the water quality of the tested civil wells is alkaline with a pH value of 8.88; this contrasts with water taken from the "boiling wells", whose lake and well water is acidic with a pH value of 4.52-6.54. With regard to the six "boiling wells", observation of the iron content in the three turbidity-water wells reveals that it is relatively high (with an average value of 13.23 mg/L); this contrasts with the iron content of the three limpid-water wells, which is relatively low (with an average value of 5.75 mg/L). It can therefore be suggested that the main cause of turbidity water forming in the three wells may be the rapid oxidation of well water (with high iron content) into ferric iron precipitation, and it can in turn be suggested that this results from exposure to air.

Table 2 Hydrometetic components (mg/L) of "boiling well" and civil well water samples in Danyang City, Jiangsu Province

	Bicarbonate	ree carbon ioxide	Calcium ion	Iron	manganese	Total dissolved solids	Total hardness	Organic matter	pH
Boiling well 1	618	439	203.3	4.65	5.75	1012	702	not detected	6.2
Boiling well 2	1289	476	375.5	9.61	3.41	1386	1102	not detected	6.5
Boiling well 3	1214	464	356.3	2.98	1.2	1340	1044	not detected	5.6
Boiling well 4	974	453	282.5	10.96	3.03	1102	870	not detected	6
Boiling well 5	985	491	284.6	11.78	3.32	1118	876	not detected	4.5
Boiling well 6	979	447	292.2	16.96	3.74	1102	915	not detected	5.1
Lake water	150	＜4	50.9	0.58	0.07	326	186	Methylene chloride	5.2
Civil well	156	＜4	57.7	＜0.05	0.02	396	196	Chloroform	8.8

The content of light rare earth components (Y, La, Ce, Pr, Nd, Sm, etc.) in "boiling well" water is several hundred times higher than that found in civil wells water (Fig. 9) and several to dozens times higher than that found in lake water. Closer analysis reveals that the rare earth component of civil wells water taken from the research area is basically the same level as underground water extracted from the Hetao Plain of Inner Mongolia[6], Datong Basin[7], Nanjing's Jiaozi Mountain Karst Area[8] and Xutuan's Coal Mine Area in northern Anhui Province[9]. The recording of 0.0186-3.4470 μg/L indicates that the content of rare earth elements in the groundwater of "non-boiling wells" is generally low.

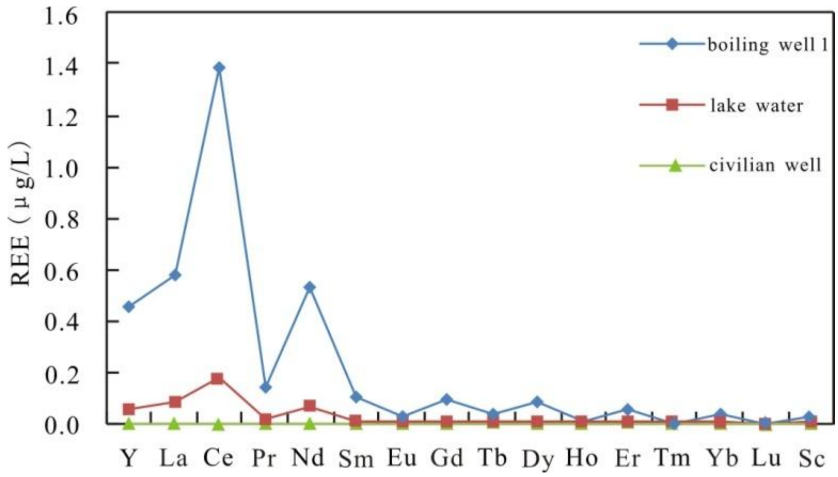

Fig.9 comparison of rare earth content (μg/L) between "boiling well" and civilian well water and lake water in Danyang City, Jiangsu Province

3.3 The gas of "boiling wells" has special composition with persistent low TVOC content and high radon content.

It has been found that CO_2 is the main component of the boiling gas from the "boiling wells". When burning candles, lighters and other combustibles are placed into the "boiling wells", they usually extinguish after descending about 10 centimeters below the wellhead.

Measurement of the organic matter in boiling gas extracted from the "boiling wells" reveals that the TVOC content is persistently low, mainly falling between 0.003 ppm and 0.02 ppm, and recording an average of 0.013 ppm. The TVOC content of "boiling well 5", in contrast, mainly falls between 0.016 ppm and 0.029 ppm and records an average of 0.014 ppm. While the TVOC content fluctuates sporadically over time (Fig. 10, Fig. 11, Table 3), it always exists; in contrast, this content is not detected in the air of surrounding lake and civil wells water.

Date Time	TVOC(ppm)
2011/9/28 14:24:06	0.007
2011/9/28 14:24:16	0.006
2011/9/28 14:24:26	0.003
2011/9/28 14:24:36	0.011
2011/9/28 14:24:46	0.014
2011/9/28 14:24:56	0.009
2011/9/28 14:25:06	0.008
2011/9/28 14:25:16	0.005
2011/9/28 14:25:26	0.013
2011/9/28 14:25:36	0.007
2011/9/28 14:25:46	0.006
2011/9/28 14:25:56	0.010
2011/9/28 14:26:06	0.008
2011/9/28 14:26:16	0.010
2011/9/28 14:26:26	0.006
2011/9/28 14:26:36	0.012
2011/9/28 14:26:46	0.008
2011/9/28 14:26:56	0.009
2011/9/28 14:27:06	0.013
2011/9/28 14:27:16	0.016
2011/9/28 14:27:26	0.008

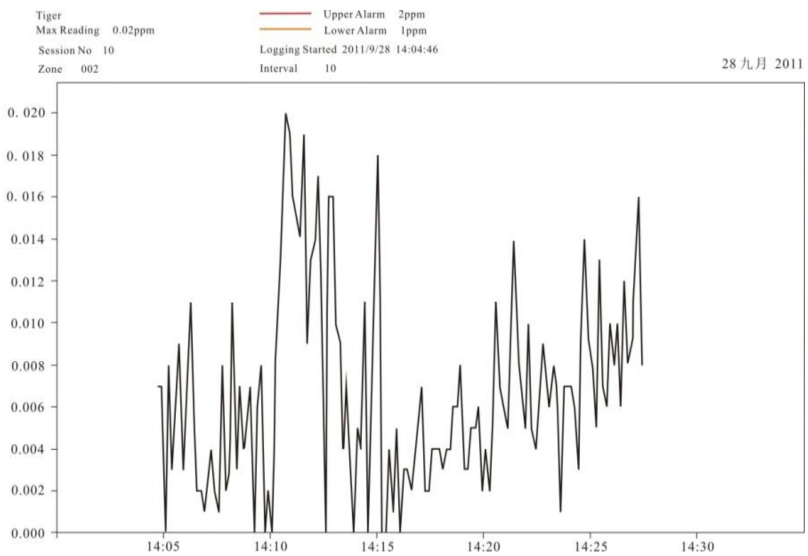

Fig.10 Variation of total volatile organic compounds (TVOC) in "boiling well 1" in Danyang City, Jiangsu Province

In this study, radon gas measurements were taken from the "boiling wells" and surrounding areas. Radon gas is often used as an indicator element for deep information sources because it has stable chemical properties, strong migration ability and also the ability to migrate to active faults and surrounding fractured zones and reach the surface. Radon gas measurement makes it possible to identify the spatial location of underground active faults and to evaluate the activity of faults. It has been widely adopted in both local and international theatres, where the intensity, range and composition variation of radon gas emission from faults has been used to find the spatial distribution location of faults (belts) in the coverage area and to analyze and evaluate their relative activity[10-15]. Chinese scholars have also tried to apply this method in urban active fault detection, and some preliminary results have been achieved.

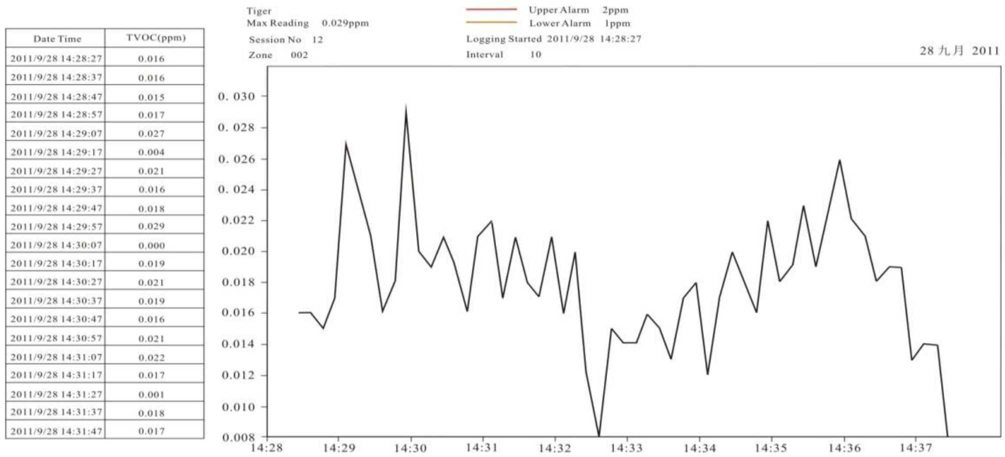

Fig.11 Variation of total volatile organic compounds (TVOC) in "boiling well 5" in Danyang City, Jiangsu Province

Table 3 Average TVOC content of different water samples (unit: PPM) and their boiling and turbid states

Sample no.	TVOC average	Boiling state	Turbid state
Boiling well 1	0.013	Boiling strongly	Llimpid
Boiling well 2	0.021	Boiling strongly	Limpid
Boiling well 3	0.015	Boil the weaker	Limpid
Boiling well 4	0.014	Boiling strongly	Turbidity
Boiling well 5	0.017	Boil the weakest	Turbidity
Boiling well 6	0.019	Boil the weaker	Turbidity
Lake water	not detected	Without boiling	Limpid
Civil well	not detected	Without boiling	Limpid

The radon gas measurement results show that a relatively high radon gas concentration spilled from the "boiling wells" (Table 4), clearly contrasting with the radon concentration in the surrounding air, lake water and civil well water, where it was almost zero. But there were significant differences in the radon gas concentration that spilled from each "boiling well", with "boiling well 1" recording the highest concentration (962 pCi/l) and "boiling well 5" the lowest (520 pCi/l). This observed difference obviously relates to the boiling intensity of each "boiling well": that is, the more intense the boiling, the higher the radon gas concentration spilled. The intensity of boiling in "boiling wells" could be mainly controlled by the fracture pore density in the gas escape passage: the higher the fracture pore density, the more intense the boiling, with the reverse also applying.

Table 4. Radon concentration in the "boiling well" and surrounding air in Danyang City, Jiangsu Province

No.	X	Y	concentration（pCi/l)
Boiling well 1	730593	3532427	962
Boiling well 2	730587	3532425	693.5
Boiling well 3	730587	3532424	709
Boiling well 4	730586	3532423	857
Boiling well 5	730588	3532423	520
Boiling well 6	730589	3532420	843
Ambient air	——	——	0

Four abnormal high-value points (Fig. 12, Fig. 13) were also found in the measurements of soil radon gas profiles taken from the "boiling wells". When combined with the distribution of geological structure in the research area, these results demonstrate that the four high-value points coincide with the four intersection positions of inferred four hidden faults (specifically F8, F7, F3 and F6 – see Fig. 14) and the soil radon measurement lines in the research area. The "boiling wells" are located at the intersection of F3 and F6 and the abnormal high-value points of radon gas coincide with the distribution of faults.

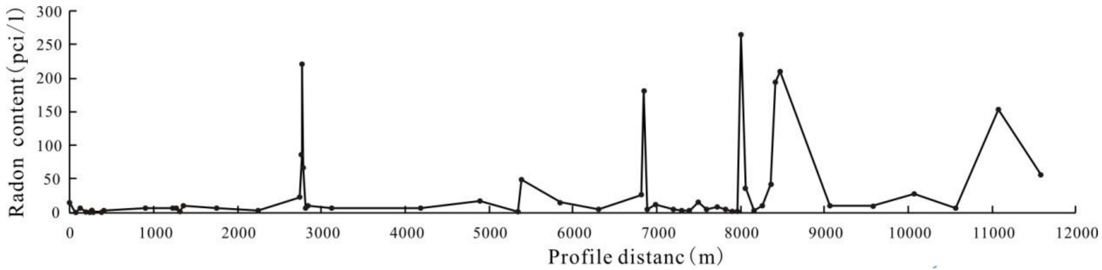

Fig.12 An abnormal profile of radon concentration in soil around the "boiling well" in Danyang, Jiangsu province

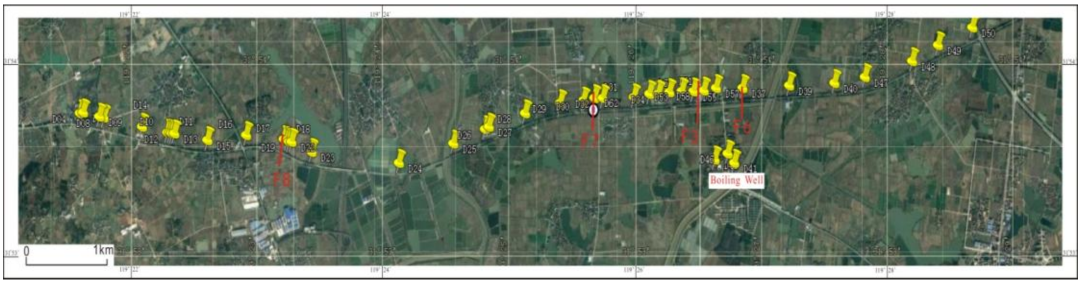

Fig**.13** Soil radon measurement line and fault location map around the "boiling well" in Danyang, Jiangsu province

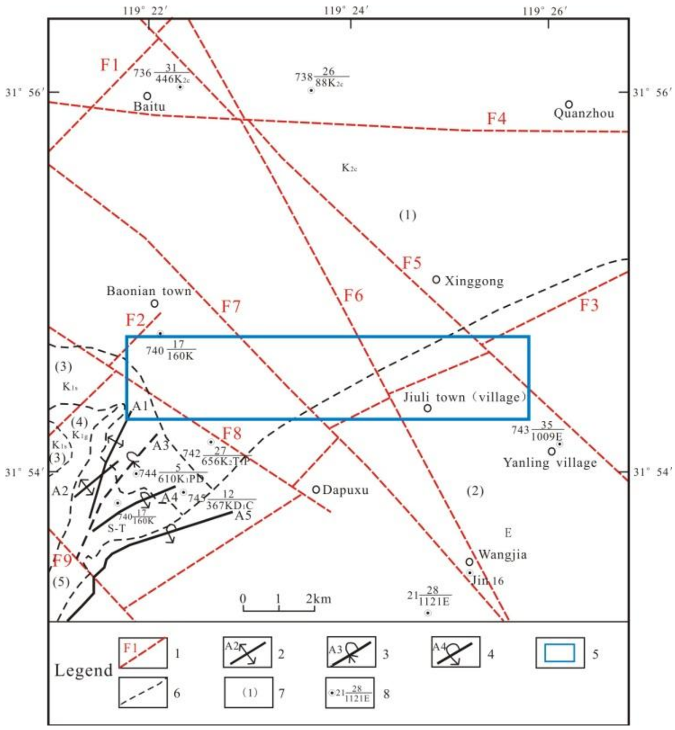

Fig. 14 Geological structure diagram of the study area in Jiuli Town

1. Inferred concealed faults and their serial Numbers; 2. Concealed anticline; 3. Inverted steering oblique structure; 4. Inverted anticline; 5. Research area; 6. Boundary lines of basins, depressions and mountains;7. number of basin (①③④) , depression (②) and mountain (⑤) ; 8. Drilling location and number

It is found that "bubbles" occur in "boiling wells", lakes, ponds and trenches along the fault strike (Fig. 15). The high-density resistivity profile also reflects the phenomenon of low resistivity due to the relative accumulation of gas in the fault distribution area (Fig. 16). IE810005

Fig. 15 bubbling phenomenon in "boiling well" and lakes and ponds in Danyang City, Jiangsu Province
a. "bubble" in the lake five meters away from the boiling well; b. "bubbles" in ponds 20 meters away from the boiling well; c. Measurement of total volatile organic compounds in boiling well 1; d. bubbling phenomenon in boiling well 2

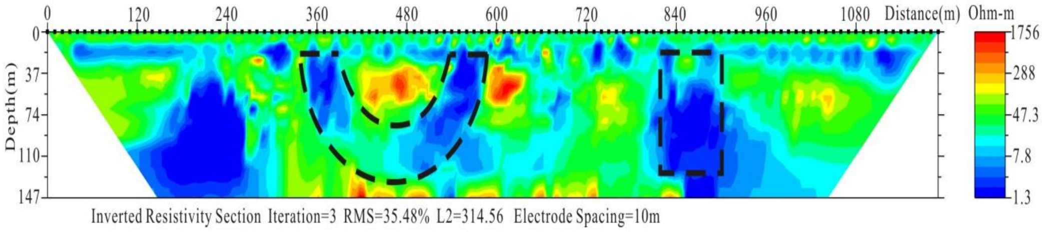

Fig. 16 "boiling well" and its peripheral high-density resistivity profile (gas concentration in blue low-resistance zone) in Danyang City, Jiangsu Province

IV. Discussion

4.1 Formation causes of CO_2 in "boiling wells"

CO_2 enrichment in basin strata was once a key preoccupation for domestic and international researchers in the fields of geoscience and environmental science [16-23]. Previous studies engaged with CO_2 gas reservoirs and high CO_2-containing oil and gas reservoirs in eastern China and offshore shelf basins [24-29], with specific emphasis on CO_2 gas reservoirs formed in the Early Tertiary-Late Mesozoic basins in eastern China and CO_2 gas reservoirs and high CO_2-containing oil and gas reservoirs (which formed near the deep-large fault in the Tertiary East China Sea Basin and the Pearl River Estuary Basin, which is located in coastal waters). These studies concluded their CO_2 is mainly the mantle-magmatic origin type.

At the global level, the distribution of mantle-derived CO_2 emission sites is also consistent with seismically active fault zones [23, 27-32]. Zhu Yuenian and Wu Xinnian (1994) [33] study the distribution characteristics of high CO_2-containing natural gas across the world, and find that the accumulation of CO_2 gas is closely related to the distribution of deep-large fault zones, and contend its distribution was obviously controlled by large regional faults. It is obvious that the "boiling wells" are located on Maodong fault line and its secondary faults. It can also be inferred that the source of CO_2 may be related to the gas-leading role of the fault zone, in possible combination with the boiling phenomenon of "bubbles" in lakes, ponds and ditches near the "boiling wells"

4.2 Formation causes of radon gas in "boiling wells" and light rare earth enrichment in groundwater

Radon gas measurement, conceived as a method of studying hidden faults, has attracted the attention of both local and international geoscientists [10, 12, 15]. Scholars in the United States and Japan have successfully applied this method to the study of faults activity, including to the San Andreas fault and the central large fault [13]. Some Chinese scholars have also attempted to apply this method to the detection of urban faults, and some preliminary results have been obtained [11, 14, 34-35]. Radon measurements conducted in "boiling wells" and surrounding areas demonstrate high abnormal radon gas values in the "boiling wells" and soil radon profiles, which are precisely related to secondary faults in the Maodong fault zone. These results support to the claim that radon gas comes from the deep part and leaks along the faults.

The tests of boiling gases from "boiling wells" confirm that low-content TVOC is persistently evidenced in all six "boiling wells" gases. However, the same phenomenon has not been detected in nearby civil wells, and no man-made organic pollution has been found in and around the "boiling wells", and this raises the possibility that it may have originate in deeper deep. Abiogenic inorganic hydrocarbons that occur in the deep mantle degassing zone have been studied by many scholars [36], who have put forward Fault Controlling Hydrocarbon Theory [37]. The continual occurrence of low-content TVOC in the "boiling well" gas may also reflect its origin in the deep mantle.

The content of light rare earth components (Y, La, Ce, Pr, Nd, Sm, etc.) in water obtained from "boiling wells" water is several hundred times higher than civil wells water and several times higher than lake water. This raises the question of if the high content of light rare earth can also be traced to deep earth. Potential enlightenment is provided by Niu Hecai et al, 2002 [38] and Tian Shihong et al., 2006[39]. They claim that there is a genetic relationship between the light rare earth mineralization and the mantle process in the light rare earth elements deposits such as Maoniuping, Dalucao and Panzhihua deposits, which are concentrated in the Panzhihua-Xichang rift zone. The light rare earth elements ore-forming fluids of light rare earth elements deposits are deep-sourced and their ore-forming materials come from the mantle.

4.3 Cutting depth and Quaternary activity of Maoshan fault

The Maoshan fault (including the Maodong and Maoxi faults) is composed of a series of normal staggered faults that run parallel to each other. The faults generally follow a north-north-east trend and lead in a southeast direction. Most of the preceding contributions agree on the cutting depth and activity of the Maoshan fault, and Eocene and Miocene basalts are intermittently distributed along the faults [40]. The basalt contains the upper mantle material-diopside xenolith, and it can be speculated that the depth of the magmatic rocks is below 50 km, and this reflects the fact that the fault depth has reached the mantle [4, 41-43]. The main active age of the Maoshan fault is the late Pleistocene, but earthquakes with magnitude above 6 (on the Richter Scale) have occurred along it over the past hundred years, and this suggests it was still active in the late Quaternary [4, 42, 44-46]. Ye Hong et al. (1980)[47] suggest that the relative vertical movement rate between the Mao Mountains (410 meters above sea level) and Maodong Basin was about 1-2 mm per year, while Sun Shoucheng et al. (1983)[48] claim that the average displacement rate was 2-2.5 mm/year. Wang Bin et al. (2008)[49] conclude that the Maoshan fault zone with large depth is an important gravity gradient zone and aeromagnetic negative anomaly zone in southern Jiangsu. The fault zone mainly shows thrusting activity before Cenozoic or during Mesozoic and demonstrates normal faulting activity since Quaternary.

4.4 Formation mechanism of "boiling wells"

In taking into account the preceding research and analysis, the authors suggest that the positions of boiling bubbles in "boiling wells", adjacent lakes, ponds and ditches are all distributed within Maodong's active fault zone and its secondary faults zone. The CO_2 gas emitted from "boiling wells", a small amount of radon gas, persistent low-content TVOC and light rare earth enriched in the groundwater of "boiling wells" may all belong to the deep source of the mantle that rises along the fault zone (Fig. 17). The "boiling wells" are not hot spring spots. The well water mainly comes from the phreatic aquifer, and the temperature of well water in "boiling wells" is consistent with local wells. The overflow of a large number of gases leads to the boiling phenomenon observed in "boiling wells". The different flavors of "boiling wells" are due to the different contents of free carbon dioxide, bicarbonate ions, pH value, calcium ions, total soluble solids, total hardness, iron, manganese and other chemical components in the water. The limpid and turbidity of "boiling well" water are mainly related to the content of ferrous in the water. The main reason for the formation of turbidity well water is that water with high ferrous content can be oxidized into a large amount of ferric iron precipitation as a result of exposure to air.

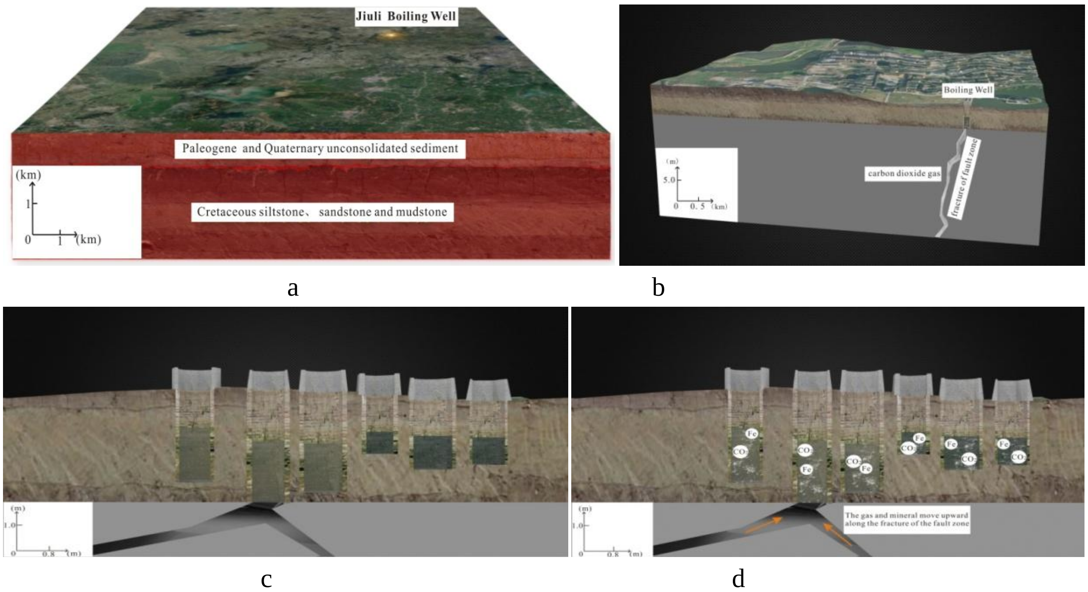

Fig. 17 Schematic diagram of formation mechanism of "boiling well" in Danyang City, Jiangsu Province

(a)—Stratigraphic structure (upper Quaternary and Paleogene, lower Cretaceous siltstone, sandstone and mudstone)；(b)—Forming fault zones and fractures；(c)—A group of Wells dug above the fault；(d)—Gas and minerals move up the fault zone

V. Conclusions

(1) In Jiuli Village, Yanling Town and Danyang City of Jiangsu Province, there are "boiling wells" that are over 2000 years old, whose main boiling gas is CO_2. In addition, there are also high abnormal radon gas and TVOC components that are not found in nearby "non-boiling wells".

(2) The contents of free carbon dioxide, calcium, iron, manganese, total dissolved solids, total hardness, bicarbonate and rare earth elements in the "boiling well" water samples are obviously higher than those found in other civil water wells around the "boiling wells". The content of light rare earth components (Y, La, Ce, Pr, Nd, Sm, etc.) in "boiling well" water is several hundred times higher than that civil wells water.

(3) The "boiling wells" are not hot spring spots and their cause of formation can be clearly distinguished from Spouting Spring in Jinan and Pearl Spring in Nanjing. The existence of "boiling wells" is closely related to the Maodong active fault. A basalt rock body and a secondary fault of the Maodong active fault are located in the deep underground of "boiling wells". Gas components, such as boiling CO_2, radon gas and TVOC in "boiling wells", and also light rare earth elements in water samples from "boiling wells", are mainly derived from the deep crust or upper mantle: they rise from here, travel along the fault zone and then escape from the surface.

(4) The water taste of six "boiling wells" is different due to the different pH value of "boiling well" water and different chemical components in the water of each "boiling well", which include free carbon dioxide, calcium, iron, manganese, and so on. The "three limpid and three turbidity" of "boiling well" water is mainly related to the iron content in well water. The main reason for the turbidity of well water is that water with high iron content can be oxidized to the precipitation of ferric iron due to exposure to air.

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