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

Geothermal Resources and Potential Area for High-temperature Exploration in Yunnan, China

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Keywords: Himalayan geothermal zone, high-temperature hydrothermal systems, Tengchong, Late Cenozoic volcano

ABSTRACT

Yunnan is one of the most potential areas of geothermal resources in China. There are more than 800 springs with temperature ranging from 25 ℃ to 100℃ and natural heat emission up to 2.1×10^{16}J/yr. Hydrothermal systems are mostly controlled by fracture zone or volcano-magmatic activity. The medium- to 1ow-temperature hydrothermal systems are dominant in eastern Yunnan, which is related to active faults. While high-temperature hydrothermal systems are dominant in western Yunnan, which is associated with volcanic activity. The preliminary estimation of thermal energy stored in geothermal systems with the depth above 1km was about 1,893 EJ. Tengchong is the most potential geothermal area for electricity generating. The total electrical energy of the five high-temperature hydrothermal systems was estimated up to 450MW. Although geothermal drilling has not obtained the expected high-temperature fluid, the results from geophysical and geochemical exploration suggested that high-temperature geothermal exploration in western Yunnan should be focused on Tengchong area.

1. INTRODUCTION

Yunnan Province is located in the southwest of China, covering an area of about 394,000km^2. About 94% of the area are mountainous areas. Geothermal resources are abundant in this area. About 800 thermal springs with temperature ranging from 25 ℃ to 100℃ occur throughout the area. Their total flow rate is about 7587.62 l/s and natural heat emission is up to 2.1×10^{16}J/yr. (Yin et al. 2006). Yunnan could be divided into western Yunnan and eastern Yunnan by the Jinshajiang-Honghe fracture zone (Figure 1). Medium- to 1ow-temperature hydrothermal systems are dominant in eastern Yunnan while high-temperature hydrothermal systems are dominant in western Yunnan. The preliminary investigation of thermal spring was in the late 1980's by the Commission on Multidisciplinary Exploration of Natural Resources, Academia Sinica (Tong and Zhang 1994). But the work was only limited within western Yunnan. Zhuang (1987) firstly reported the geothermal resources in Yunnan from studying 654 thermal springs and borehole. Chen et al (1994) demonstrated the geothermal resources formation characteristics and potential evaluation. Liao and Zhao (1999) discussed the geothermal potential of western Yunnan based on the study of selected geothermal field in the Tibet—Yunnan geothermal zone. In addition, many geothermal works, such as geophysical and geochemical survey have been carried out in western Yunnan. Recently, the deep drilling for geothermal exploration has been conducted in western Yunnan, and some available information has been obtained.

The purpose of this paper is to present the outline of geothermal resources and the progress of geothermal exploration in Yunnan, especially in the geothermal fields in western Yunnan. Some discussion will be focus on the further high-temperature geothermal exploration in this area.

2. GEOLOGY AND GEOTHERMAL BACKGROUND

Geologically, Yunnan is located in the composite part of the Himalayan-Tethys structural domain and the circum-pacofic structural domain, with very complicated geological structures and intensive Cenozonic magmatism. The western Yunnan is the southern part of Tibet Plateau and a fold area. The strata from Paleozoic to Mesozoic are composed of detrital and carbonate rock, and interbed of volcanic rock. These rocks have been affected by metamorphism. The Cenozoic strata are sporadically distributed and consist of a series of detrital rocks. There are more than 50 late Cenozoic volcanoes with a cover area about 1,000km^2 in Tengchong area. The volcanic activity could be classified into four stages, which were eruption at 2.93 Ma, 0.81 Ma, 0.31 Ma and 0.13Ma, respectively. The eastern Yunnan is a platform and southeast fold are. The strata from Sinian system to Quaternary system are dominated by carbonated and detrital rock. In addition, the Permian basalt is distributed widely.

The active faults are developed and the high magnitude earthquakes took place frequently in the study area. There are about 28 large active faults, in which the Honghe—Jinshajiang fault frame the boundary of tectonic stress field and divide Yunnan into two fault block, western Yunnan and eastern Yunnan. The large faults in western Yunnan include Nujiang fault, Langcangjiang fault and the Honghe fault. The western Yunnan fault block is continually moved and compressed to the northeast, and most secondary faults are dextral faults. While the eastern Yunnan fault block is continually moved and compressed to the northwest, and most secondary faults are sinistral faults. Recent volcanoes and faults are the main geological characteristics in western Yunnan. The recent tectonics of Tengchong are characterized by approximate N-S distribution. And the NE-trending and NNE-trending faults form an arc structure.

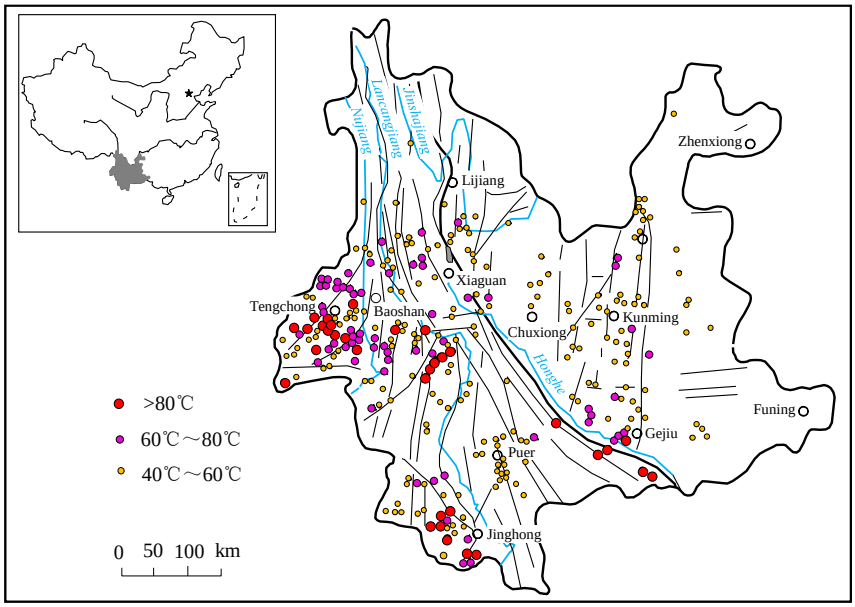

Figure 1: Study area and distribution of thermal springs (revised from Chen et al. 1994)

Geothermal background is characterized by high value of heat flow, with mean value up to 70mW/m^2. (Wu et al 1988, Wang et al 1990). Figure 2 shows the distribution of heat flow value in Yunnan. The heat flow value ranges from 75 to 120 mW/m^2 (mean value about 85 mW/m^2) in the west of Nujiang River, and from 37 mW/m^2 to 69 mW/m^2 (mean value of 51 mW/m^2) in southeastern Yunnan, and from 42 mW/m^2 to 104 mW/m^2 (mean value of 77 mW/m^2) in central and northern Yunnan, respectively. The distribution of subsurface temperature is similar to that of heat flow value (Wang et al. 1990). The high subsurface temperature occurs in the recent volcanic activity area and the west of Nujiang River. In northern Yunnan, the subsurface temperature is also high due to the active faults, but it has the characteristics of alternating distribution of high and low temperature. In southeastern Yunnan, the subsurface temperature is low since the tectonics is relatively stable.

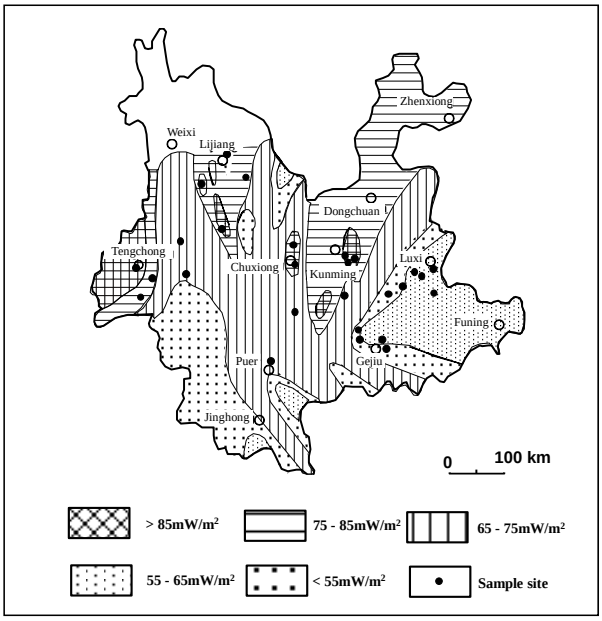

Figure 2: The Heat flow map in Yunnan (from Wang et al. 1990).

3. GEOTHERMAL RESOURCES IN YUNNAN

The geothermal systems are controlled by tectonics in Yunnan. Medium to low temperature hydrothermal systems are mainly distribute in eastern Yunnan. About 260 thermal springs were investigated in eastern Yunnan, among which 72 springs are at temperature of 41℃—80℃. The total flow rate of springs was estimated at 4,925.2 l/s with natural heat emission of 7.8×10^4 cal/s. Thermal water is chemically of the HCO_3-Na or HCO_3-SO_4-Ca type. One of hydrothermal systems that has been explored and exploited is Kunming low temperature geothermal field (Xu and Chen 2000).

High-temperature hydrothermal systems are mainly distributed in western Yunnan. About 424 springs occur in western Yunnan, including 130 springs with temperature of 25℃—40℃, 254 springs with temperature of 41℃—80℃, 25 springs with temperature 80℃—95℃ and 15 boiling springs with temperature of more than 95℃ (Zhuang 1987). The total flow rate of springs is about 2,662.4 l/s with natural heat emission of 8.7×10^3kcal/s. The hydrochemical types of thermal water are HCO_3-Ca and HCO_3-Cl-Na. The 34 high-temperature hydrothermal systems (> 80℃) were found along the Ruili-Longling arc fracture zone (Chen et al. 1994) The reservoir is composed of crystalline rocks such as granite, migrnatite, gneiss and limestone, and the reservoir temperature estimated by geothermometers was more than 150℃. The detail information of selected systems was listed in Table 1.

The geothermal resources were estimated by dividing Yunnan into four subareas (Chen et al. 1994). Total thermal energy stored in geothermal systems with an area 383900 km^2 and depth above 1km was estimated about 1,893 EJ. In Tengchong area, all the high-temperature systems are distributed along the margins of active plates and around the young volcanic flows. Figure 3 shows active tectonics and thermal springs in Tengchong area. It has been found that there were about 50 hydrothermal systems in Tengchong geothermal area, five of which have the potential for electricity generating, namely Langpu, Hot Sea (Rehai), Ruidian, Panzhihua and Heishihe. The total electricity power of five systems was estimated about 450MW by Guo et al. (1989). The most potential geothermal field is Hot Sea (Rehai) with the estimated electricity power of 233.5MW.

The Hot Sea geothermal field lies only 11km southwest of Tengchong , covering an area of about 100km^2, including two geothermal manifestation areas, Reshuitang in the west while Liuhuangtang in the east. The reservoir is composed of sandstone, gneiss and granite. Hot water with a maximum temperature of 97℃, emerges from the granite. The chemical type of geothermal water is mainly HCO_3-Cl-Na. The gas was composed of CO_2, H_2S, H_2, N_2 and O_2. Liuhuangtang geothermal manifestation area, at the elevation of 1,400—1,600m above sea level, with an area of 8.5km2, is an area with strong hydrothermal manifestation, such as boiling springs, hot water pools, fumaroles, steam grounds and thermal springs. The temperature of geothermal water ranges from 42℃－96℃. The reservoir temperature estimated by geothermometers is about 238℃. Reshuitang manifestation area is located at an elevation of 1,100—1,500m and covers about 4.3 km^2, Fossil travertine and sulfur are widely distributed in this area.

Table 1: High-temperature springs (> 80℃) in western Yunnan (from Chen 1994)

No	Name	Location	Temperature (℃)	Flow rate (l/s)	TDS (g/l)	Water type
1	Bangbeng, Ruili	97° 56 ′ E, 24° 03 ′ N,	101	3.0	1.02	Cl-Na
2	Humeng, Yingjiang	98° 07 ′ E, 24° 44 ′ N,	82	2.64	0.24	HCO3Na
3	Lanniba, Yingjiang	97° 55 ′ E, 24° 47 ′ N,	85	0.9	0.35	HCO3-SO4-Na
4	Mangke, Yingjiang	98° 07 ′ E, 24° 45 ′ N,	81	10.99	0.04	HCO3Na
5	Banazhang, Longling	98° 38 ′ E, 24° 37 ′ N,	100	9.01	0.71	HCO3Na
6	Chaoyang, Longling		81	18.28	0.44	HCO3Na
7	Panzhihua, Tengchong	98° 28 ′ E, 24° 43 ′ N,	96.7	1.51	0.76	HCO3Na
8	Longwozhai, lianghe	98° 16 ′ E, 24° 47 ′ N,	86	7.91	0.90	HCO3Na
9	Liuhuangtang, Rehai	98° 26 ′ E, 24° 55 ′ N,	97	0.98	2.48	Cl-SO4-Na
10	Zaotanghe, Rehai	98° 26 ′ E, 24° 55 ′	98	13.33	1.44	HCO3-Cl-Na
11	Huangguaqing, Rehai	98° 26 ′ E, 24° 55 ′ N	93	0.83		
12	Langpuzhai,Tengchong	98° 23 ′ E, 24° 55 ′ N,	100	7.98	1.14	HCO3-Cl-Na
13	Bailaotang, Baoshan	98° 46 ′ E, 25° 10 ′ N,	86	4.1	0.63	HCO3-SO4-Na
14	Ruidian, Tengchong	98° 28 ′ E, 25° 27 ′ N,	92	3.52	1.07	HCO3-Na
15	Ruidian,Tengchong	98° 28 ′ E, 25° 27 ′ N,	88	1.07	1.24	HCO3-Cl-Na
16	Taiping, Yunlong	99° 08 ′ E, 25° 53 ′ N,	91.5	6.35	0.60	HCO3-Na
17	Yongxin, Fengqing	99° 54 ′ E, 24° 46 ′ N,	96	3.33	0.34	HCO3-Na
18	Juanheqiao, Fengqqing	99° 53 ′ E, 24° 46 ′ N,	96	7.18	0.23	HCO3-Na
19	Malutianba,Yunxian	99° 57 ′ E, 24° 07 ′ N,	98	8.93	0.53	HCO3-Na
20	Xingfu, Yunxian	99° 59 ′ E, 24° 10 ′ N,	98	3.80	0.51	HCO3-Na
21	Dakunbeng, Yunxian	100° 02 ′ E, 24° 21 ′ N,	96	21.92	0.59	HCO3-Na
22	Xiaodingxi, Yunxian	100° 18 ′ E, 24° 39 ′ N,	92	0.97	0.41	HCO3-Na
23	Heishan, Lancang	100° 21 ′ E, 22° 18 ′ N,	83	2.5	0.36	HCO3-Na
24	Yunnan, Lancang	99° 59 ′ E, 22° 40 ′ N,	93	4.0	0.59	HCO3-Na
25	Hula, Lancang	100° 11 ′ E, 22° 16 ′ N,	83	25.6	0.47	HCO3-Na
26	Mengman, Menghai	100° 08 ′ E, 22° 18 ′ N,	99	0.61	0.68	HCO3-SO4-Na
27	Mansao, Menghai	100° 23 ′ E, 21° 52 ′ N,	91	2.0	0.39	HCO3-Na
28	Jinghong	100° 42 ′ E, 21° 44 ′ N,	103	5.68	0.37	HCO3-Na
29	Wana, Yuanjiang	101° 55 ′ E, 23° 31 ′ N,	92	4.07	0.15	HCO3-Na
30	Reshuitang, Yuanyiang	102° 41 ′ E, 23° 11 ′ N,	81	3.8	0.38	HCO3-SO4-Na
31	Kele, Gejiu		>90	10.0	0.30	HCO3-Na
32	Jinping	103° 29 ′ E, 22° 55 ′ N,	90	6.53	0.78	HCO3-SO4-Na
33	Asizhai, Jinping	103° 26 ′ E, 22° 56 ′ N,	83	1.69	1.0	HCO3-SO4-Na

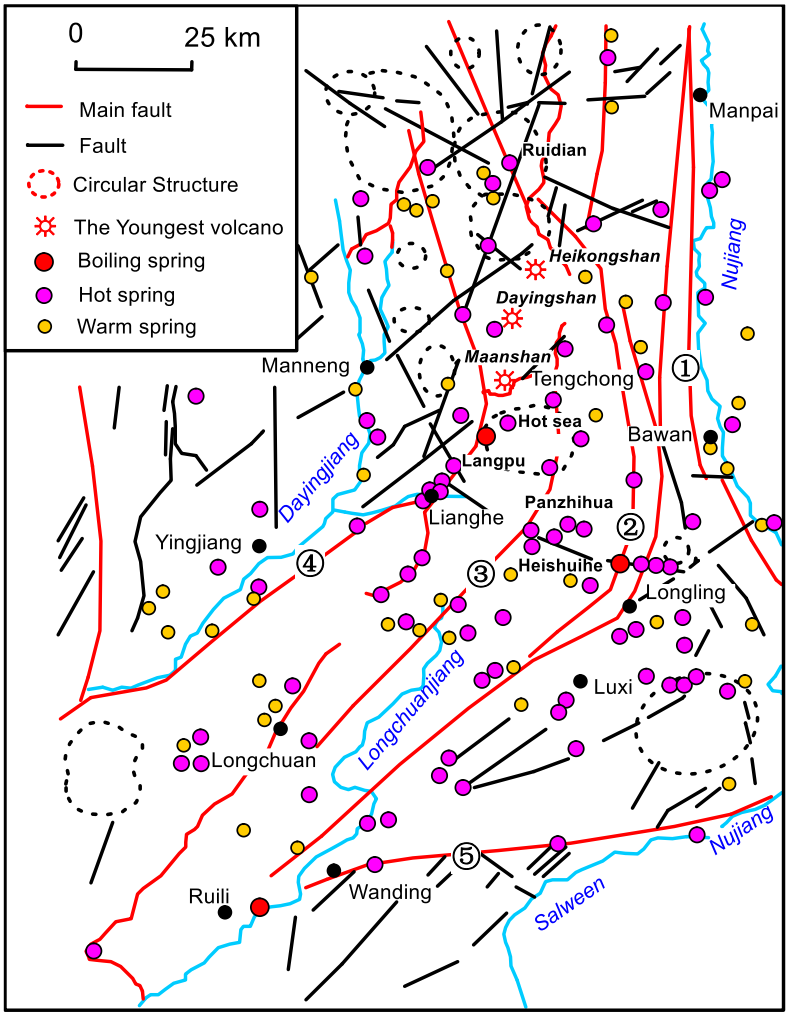

Figure 3: Active tectonics and thermal spring distribution in Tengchong area (Revised from Liao and Guo 1986).① Nujiang fault, ②Longchuanjiang –Longling-Ruili fault, ③ Xiaolongchuan-Tengchong-Ruidian fault, ④Lianghe-Guyong fault, ⑤Wanding fault

3. POTENTIAL AREA FOR HIGH-TEMPERATURE EXPLORATION

Geophysical and geochemical studies suggest that the structure of lithosphere and the position of the asthenosphere varies considerably in Western Yunnan, which could have significantly influenced the occurrence of high temperature geothermal fields. Usually, the high-conductivity and low-velocity layers are considered to be fluid-rich layers, which can be inferred as the upwelling zone of the asthenosphere of the mantle. The results from geophysical computerized tomography showed that low-velocity perturbation of S-wave occurred in the depth of 70km in the west of Jinshajiang-Honghe fracture zone (Li et a1. 2016). The data of magnetotelluric sounding (MT) suggested that the depth of high-conductivity layer in upper mantle is about 70-80km in Tengchong, which may indicate the upper interface of asthenosphere (Sun et al. 2003, Wang et al. 2017) .Wang et al. (2018) found that the occurrence of high-temperature geothermal manifestations is associated with high value of helium isotope ratios and the upwelling zone of asthenosphere (Figure 4), e.g. the highest helium ratios are 5.91Ra and 9.34Ra in the Quaternary volcanic area of Tengchong and Ning'er, respectively. The contribution of mantle-derived helium was estimated more than 75% (Zhao et al. 2012). The geothermal anomalies of the two areas are related to magma chambers and partial melting in the crust.

Since 1980, many geophysical and geochemical surveys have been carried out in the Hot Sea geothermal field. Some shallow borehole temperatures had been measured. Based upon the deep seismic sounding profiles carried out in the Tengchong volcano area, a low-velocity anomaly zone exists in the upper crust, which may be related to the magma differentiation (Wang and Gang 2004). The magnetotelluric sounding suggests that a high-conductivity layer of 20km thickness at a depth of 7km, probably is the cooling magma chamber (Ding and Fang 1996). In 1998, the first deep drilling for geothermal water was carried out in the western part of the Hot Sea. The depth of borehole is 1,640m with bottom temperature of 143.5℃. The expected high-temperature geothermal fluid, however, was not obtained due to the low permeability of the reservoir. It seems to be impossible to obtain the fluid with temperature of more than 180℃ in the western part of Hot Sea. Yang et al. (2013) suggested that the Hot Sea is not vertically connected to the deep mantle, and its heat may laterally (in the subsurface) come from the other two areas which are vertically connected with the deep mantle.

Seismic reflection profiling provides some information about geothermal fields. Figure 5 shows the results of inversion for 3-D velocity structure in Tengchong. The data suggest that a low-velocity zone occurs at the depth of 4-10 km in the east of Hot Sea. Cao et al. (2018) presented a gravity and magnetic inversion profile in Tengchong volcanic field. It also shows a low- velocity zone at the depth of 4-10 km in the east of Hot sea, which is probably a magma chamber and located in Qushi-Puchuan high gravity anomaly area.

The results of current studies from SinoProbe project suggested that three magma chambers exist in Tengchong: 1) Wuhe-Xinhua-Puchuan-Tuantian, possibly at a depth of 4-12 km; 2) Langpu-Hot Sea-Maanshan, possibly at a depth of 7-27 km; 3) Mazhan-Qushi at possibly at a depth of 12 km. In 2013, a pre-pilot hole of SinoProbe project was completed at Mazhan, about 20 km north of Tengchong. The borehole temperature was measured 74℃at the depth 1222 m.

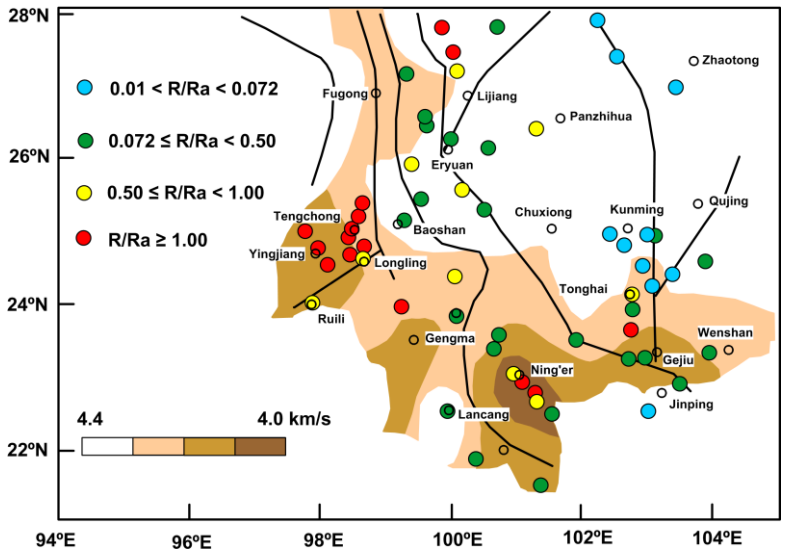

Figure 4: The distribution of helium isotope ratios and S-wave velocity structures of the upper mantle in Yunnan (from Wang et al. 2018)

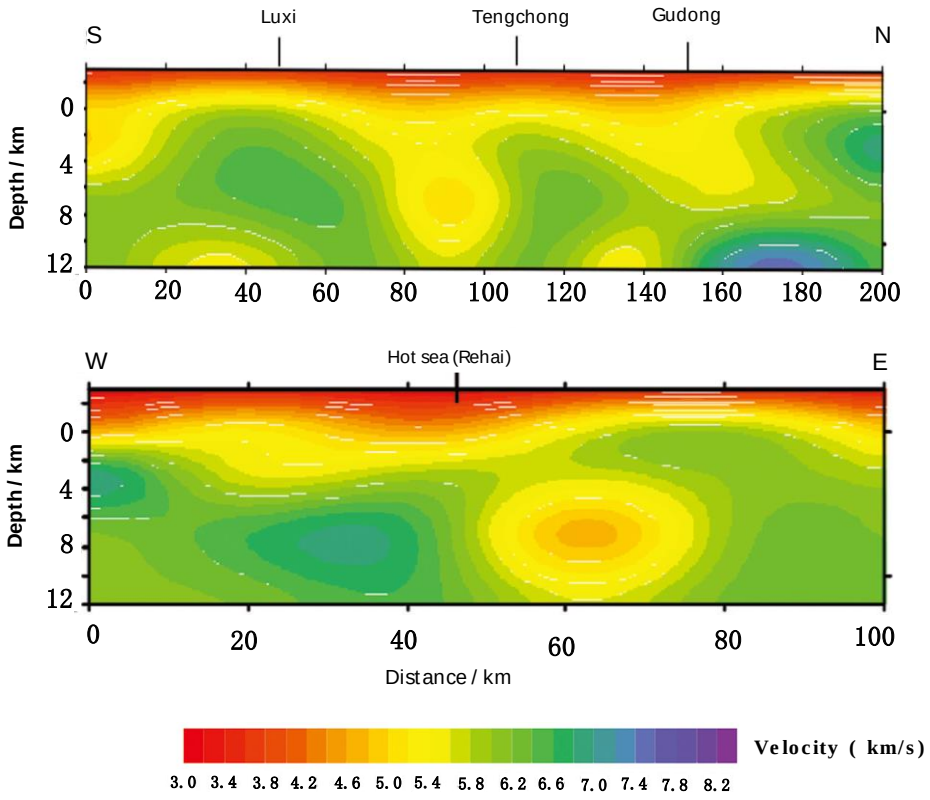

Figure 5: Seismic profile and velocity structure (from Cao et al. 2018)

4. CONCLUSIONS

The geothermal anomaly area in western Yunnan is distinct from those of the Yarlung Zangbo River valley or north-south-trending suture rift zone in Tibet and the Sunda trench-arc system in the southeast. The deep geological conditions for the formation of volcano and geothermal anomaly in Tengchong are associated with the shallow depth of the asthenosphere, and the occurrence of a low-velocity and high- conductivity layer. The helium isotope suggested that the helium derive from mantle in Hot Sea. The geophysical studies suggested that the depth of asthenosphere is about 60-80 km in Tengchong. In addition, the thickness of lower lithosphere is changeable with minimum thickness about 20km in Tengchong-Baoshan area. Thus, the possibility that some area have similar geological conditions to those of Tengchong area cannot be ruled out in western Yunnan. The spatial variations on the structure of lithosphere and crust will affect the occurrence of high-temperature geothermal field, which will be related to the exploration risk and development benefit. Although geothermal drilling has not obtained the expected high-temperature fluid, the results from geophysical and geochemical exploration suggested that high-temperature geothermal exploration should be focused on Tengchong area in western Yunnan.

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