A CONCEPTUAL MODEL OF THE REHAI (HOT SEA) GEOTHERMAL FIELD IN TENGCHONG, YUNNAN PROVINCE, CHINA

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SUMMARY - The Rehai (Hot Sea) Geothermal field of Tengchong County, Yunnan Province is the largest one in the Chinese mainland. Based on results of geological, geochemical and geophysical reconnaissance surveys since 1973, a conceptual model of the Rehai field can be built. The cap rock of the Rehai field is composed of Miocene stratum about 300 m thick and the reservoir rocks are constituted by a seismic low speed layer within the Precambrian Gaoligongshan Group beneath the surface to about 1500m. The heat source of the field could be a cooling magma pocket with a thickness of 20 km located beneath the surface in the granitic crust. The Rehai field is a hot water system with a reservoir temperature of about 230°C.

Key words: Rehai geothermal field, conceptual model, cap rock, reservoir, heat source.

1. INTRODUCTION

The Rehai (Hot Sea) geothermal field (24" 57.5' N/98° 26.5'E) is located in the western part of Yunnan Province at elevations from 1100 m to 1800 m. The earliest scientific record of thermal activity in the Rehai (Hot Sea) was in the travel diary of Xu Hong-zu in 1639. It was used for hot baths and has had minor sulfur mining since the Ming Dynasty.

Scientists at Peking University and their colleagues have described the geology and geochemistry in relation to the hydrothermal activity and have made preliminary assessments of the potential as a source of geothermal energy since 1973 (Tong et. al., 1989). During 1983-1987, the Second Hydrogeology and Engineering Geology Team of Yunnan Bureau of Geology and Mineral Resources did geological, geochemical and geophysical reconnaissance, accompanied by the drilling of ten shallow (100-400 m) holes. During the '70's and '80's evidence of a high geothermal gradient of about 100°/100 m was deduced from drillholes drilled for gold and/or uranium exploration in the southern part (Songmuqing) of the thermal field.

In order to complete the task of the 'Eighth Five Science and Technology Development Program', magnetotelluric soundings and reflection seismic exploration were conducted by Bai Denghai et. al. (1994) and Dian-Qing-Gui Geophysical Petroleum Prospecting Corporation, respectively, during 1990s. The conceptual model proposed is based on these data.

2. GEOLOGY

Volcanism began at the present site of Tengchong in the Pliocene or the Miocene and reached its peak by the Lower Pleistocene (1Ma), and lasted for the whole Pleistocene (Liao, 1989). The youngest volcanoes are Mt Maanshan, Mt Da-yingshan and Mt Heikongshan. The most recent results of K-Ar analyses give 24 ± 7 ka and 14 ± 7 ka for Mt Maanshan, 48 ± 7 ka and 62 ± 7 ka for Mt Dayingshan and 7 ± 7 ka and 14 ± 7 ka for Mt Heikongshan, respectively (Nakai et. al., 1993). The effect of this long period of volcanism is undoubtedly the geological setting of geothermal activities in Tengchong County.

The regional trend of the range is tectonically from north to south, but is superimposed upon by many circular structures. Their formation could be due to intrusions from the Jurassic to the Tertiary. The Rehai field is located inside one such circular structure.

In the Rehai field, the oldest rocks belong to the Precambrian Gaoligongshan gneiss, which was discovered in a drillhole in the southern part of the thermal field in the Zaotanghe valley. The Precambrian gneiss could be the reservoir and is covered by the Miocene sandstone and conglomerate. The stratigraphic sequence of the Rehai field is as follows (Fig. 1):

Q4 The Holocene alluvium distributed along the Zaotanghe river and the Menqianhe river;

Q2 β The Middle Pleistocene basalt located in the valleys of the above-mentioned rivers, which came from the Mt Dongdapotou volcano;

Q1 α The Lower Pleistocene andesite at the tops of the Mt Bangeshan and Mt Xidapotou;

N1 The Miocene Molasse stratum, which is mostly altered;

K2 The Late Cretaceous granite (68Ma) in the valley of the Zaotanghe river.

PCm The gneiss of the Precambrian Gaoligongshan group, which is the basement of the field.

Many faults, including the important Liuhuangtang-Huangguaqing fault, are probably good channels for the discharge of thermal fluids and are important locally in controlling hydrothermal activities including the formation of travertine and silica caps.

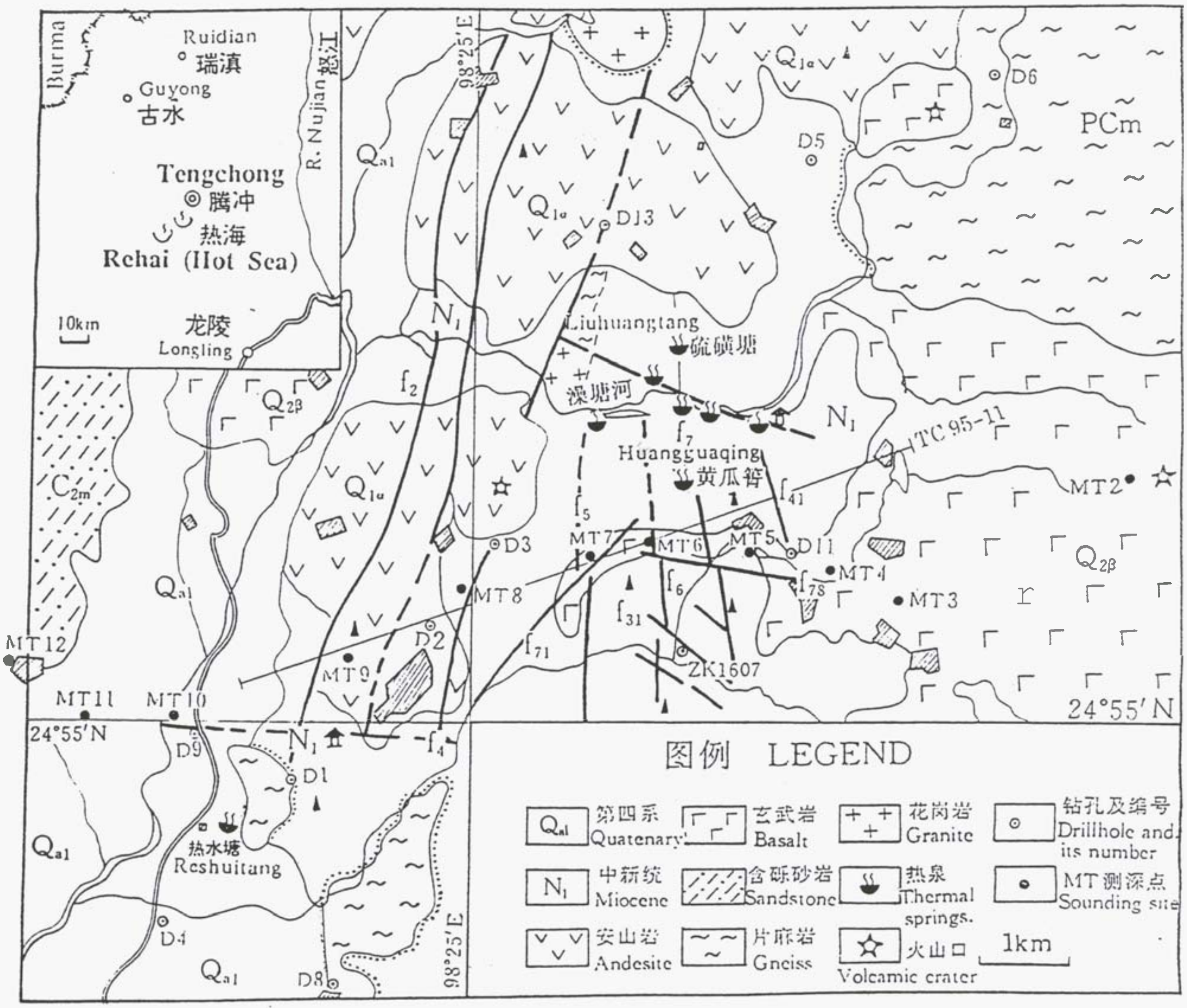

Fig. 1 Geological map of the Rehai (Hot Sea) geothermal field.

Qal----Quatenary alluvium; Q2 β --Middle Pleistocene basalt; Q1 α --Lower Pleistocene andesite; N1-----Miocene sandstone and conglomerate; C2m---Mid Carboniferous sandston- bearing gravel ; γ 5---Late Cretaceous granite; PCm--Gaoligongshan group of Precambrian.

3. THERMAL FEATURES

The thermal activity at the Rehai field can be divided into two parts: the classical region in the east and the Reshuitang (Hot Water Pool) region to the west. (There is a road connecting the eastern region to the western region, about 7 km over the mountains).

The surface manifestations of the Rehai field include boiling springs, fumaroles, steaming ground, hydrothermal alteration and gold deposits. The temperatures of the springs range from 42°C to 96°C, and the fumaroles are around 97°C. Sulfur is constantly crystallising around the orifices of the fumaroles by oxidation of H_2S. Alunogen and halotrichite are often found along the **Liuhuangtang-Huangguaqing** fault. Intermediate temperature alteration minerals, such as I-S mixed layer minerals, occur at the surface of some sites. Montmorillonite and calcite appear at the western boundary of the field. The homogenisation temperatures of the quartz inclusions range from 166°C to 300°C. The oldest ages of silica sinter or silica cap are 380 ka established by uranium series dating. Most dates are about 23 to 80 ka (Zhu, 1996).

The natural heat flow of about 180MWt for the whole area was measured by Peking University scientists.

4. GEOCHEMISTRY

The waters discharged from thermal springs were analysed. The waters can be divided into four types on the basis of their mole equivalent proportions (Liao et. al., 1991).

1. Na-Cl-HCO_3 type: This includes some boiling springs, such as Dagunguo, Yanjingquan and Dadijiao. The water is derived from deep fluid of Na-Cl type. Low magnesium is a distinguishing characteristic of this deep fluid (Table 1).

2. Na-HCO_3-Cl type: This type discharges from some hot and boiling springs. This water is a mixture of geothermal fluid and cold water;

3. Na-SO_4 type: This type comprises springs on the steaming ground and this water is a steam-heated one.

4. Ca-Na-HCO_3-SO_4 type: This includes tepid springs having a temperature of 23°C. Chemically, it is close to the cold ground water in the field.

It is assumed that the field is a hot-water system **rich** in chloride, whose subsurface boiling zone is close to the surface. Cation geothermometers indicate reservoir temperatures in the range 230°C to 275°C.

Gas samples were taken from various sites in the Rehai field. Results of analyses are listed in Table 2.

According to the composition of gases, two types of steam could be distinguished. The first type sampled from sites with a higher elevation, such as H1, R2 and R3, is rich in CO_2 and H_2S, and has higher CH_4/H_2S. It could come directly from the steam cap or condensation zone. The second type including R4, R5, R6, R7 and R8 has lower CO_2 and H_2S, as well as lower CH_4/H_2S. They are believed to be released from the thermal water reservoir (Zhao et. al., 1995).

The $^3He/^4He$ ratio of gases from the Rehai field has been studied. Gas samples were taken at 7 sites by a team. Samples were collected in November 1992 guided by Mr Liu Shibin of Peking University and analysed within 2 months by the Laboratory for Earthquake Chemistry at the University of Tokyo, Japan. The higher $^3He/^4He$ ratio in the range from 3.08 to 4.22 Ra indicates the presence of mantle-derived helium in the Rehai field. The observed $^3He/^4He$ ratios, (R/Ra, where Ra denotes atmospheric $^3He/^4He$ ratio of 1.4 x 10-6) and $^4He/^{20}Ne$ ratio together with the He concentration of the 7 gas samples, are listed in Table 3.

The calculated values listed in Table 3 indicate that all samples contain mantle-derived helium from 27% to 52% (Xu, et. al., 1994).

5. SUBSURFACE TEMPERATURES

Subsurface temperatures were measured from 19 shallow holes drilled by the Second Hydrogeology and Engineering Geology Team of Yunnan Bureau of Geology and Mineral Resources and 209 Geological Exploration Team' from 1976 to 1992. Thirteen holes ranging in depth from 100 m to 300 m. The maximum bottom-hole temperature recorded at a depth of **380** m in JK1607 at Songmuqing was 142°C. The temperature gradient of the field is from 11.5 to 100°C.100 m. The other six were shallow holes, with depths from 19 to 26 m, drilled into the seasonal variation zone.

There is insufficient data from these shallow holes to prepare a geothermal-gradient map or contour maps of the isothermal surface.

Tab. 1 Analysis of a representative group of springs at the Rehai in 1994(in mg/L)

Name	T(℃)	pH	CO_3	HCO_3	Cl	SO_4	Na	K	Ca	Mg	SiO_2	F	TDS
No.1	94	8	0	1183	673	18.5	857	125	0.08	0.03	438	20	2794
No.2	94	8	208	608	567	18.9	735	95	0.09	0.04	350	17	2348
No.3	82	7.5	0	780	365	15.7	501	68	0.82	0.14	185	10	1617

No.1 — Dagunguo; No.2 — Yanjinhquan; No.3 — Dadijia.

Sample NO.	Date	Type	CO_2	H_2S	H_2	CH_4	N·
H1	11 Dec.94	F	3570.3	15.94	3.16	28.44	34.4
R2	13Dec.94	BS	4155.6	16.73	1.57	15.90	31.2
R3	8 Dec.94	F	4541.1	26.94	3.70	34.17	53.2
R4	9 Dec. 94	BS	496.0	2.56	0.27	0.18	3.8
R5	9 Dec. 94	F	128.9	2.59	0.20	nd	o.4
R6	14 Dec. 94	BS	253.1	1.85	0.39	nd	0.7
R7	10 Dec. 94	BS	210.7	3.04	0.62	nd	2.5
R8	13 Dec. 94	BS	356.9	3.33	0.42	0.13	5.2

Location of samples: H1 — Huangguaqing; R2 — Laogunguo; R3 — NE Dagunguo;
R4 — Zaotanghe-1; R5 — Zaotanghe-2; R6 — Zaotanghe-3;
R7 — Gumingquan; R8 — Yanjingquan.

'BS' and 'F' refer to boiling spring and fumarole, respectively.

Table 3 . Helium results for samples from the Rehai field (Xiı. et al., 1994)

	Location	T (℃)	$^3He/^4He$ (R/Ra)*	$^4He/^{20}Ne$	$^3He/^4He$ $(R/Ra)^*_c$	He (ppm)	M** (%)	C** (%)	A** (%)
	Rehai-1	92.5	2.62	0.67	4.10	4.3	27	25	48
	Rehai-2	76	3.69	2.0	4.19	3.7	44	40	16
	Rehai-3	94	4.17	21	4.22	67	52	46	2
	Rehai-4	20.9	4.06	42	4.08	80	51	48	1
	Rehai-5	62.5	4.11	290	4.11	45	51	49	0
	Rehai	52.4	4.10	83	4.11	54	51	49	0
7	Resuitang	84.5	3.04	16	3.08	1.9	38	60	3

** M, C and A denote percent mantle. crustal and atmospheric helium, respectively, calculated fiom the model presented by Sano and Wakita(1985).

• R is the $^3He/^4He$ ratio of the sample and Ra is the $^3He/^4He$ of the atmosphere (1.4×10^{-6}). Measured value of R/Ra are corrected for atmospheric contamination by assuming that the neon is of atmospheric origin, according to theexpression given by Craig et al. (1978):

$(R/Ra)_{correct.} = [(R/Ra)_{meas.} \times - 1]/[X - 1]$, where $X = (^4He/^{20}Ne)_{sample}/(^4He/^{20}Ne)_{air}$

6. THE STRUCTURE OF THE GEOTHERMAL FIELD

Two separate micro earthquake surveys were made in December 1980 and March 1982 lasting 37 and 31 days respectively. A total of 334 events with magnitudes between 0 and 4.4 were recorded at the field stations. It was found that there is a thin crustal layer about 7 km thick beneath the surface of this field. Moving away from the center, the thickness of this layer gradually increases taking the shape of an umbrella, thus providing conditions for the formation of a geothermal reservoir or a magma chamber. It also shows that the seismic velocity of the upper crust in Tengchong is very unusually low with Vp of 4.62 km/s and Vs of 2.88 km/s (Liu et. al., 1986).

Magnetotelluric (MT) soundings were made at 11 stations along a 13 km profile, which crosses the Rehai field along the only road in an almost E-W direction perpendicular to the regional tectonic trend. Figure 2a is the deep section produced by 2-D inversion algorithm using TM-mode and TE-mode. Figure 2b is the observed impedance phase pseudosection for the same profile. The following is most reliable (Bai et. al., 1994):

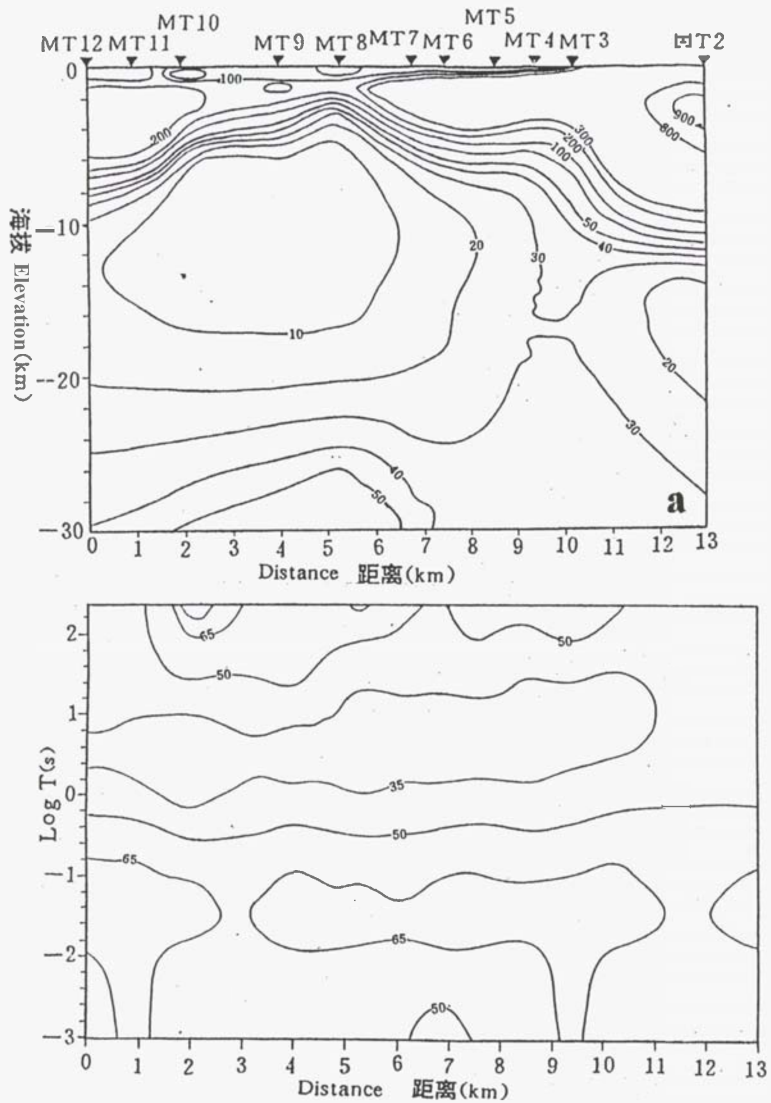

Fig. 2

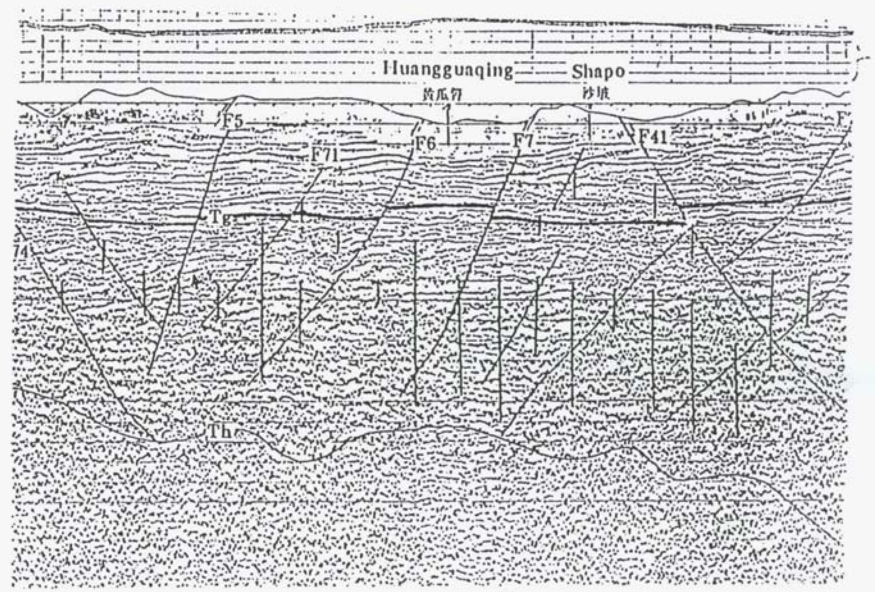

Fig. 3 Seismic reflection section at the Rehai geothermal field

1. There are two high resistivity zones on the outside stations No. 4 and No. 10 respectively. Station No. 4 lies at the eastern end of the profile and station No. 10 lies at the western end of the profile. The area between stations No. 4 and No. 10 is the Rehai thermal area.

2. Anomalously conductive structures with 5-10 Ω m exist in the upper crust from 6 to 25 km depth below the thermal area, perhaps representing a partially molten magma chamber that is the heat source for the Rehai geothermal system. The lower resistivity anomaly appears to increase below 25 km depth. The cooling magmatic body came from the upper mantle along some vertical channels.

3. There is a fracture zone between stations No. 4 and 6, where noticeable surface manifestations occur.

A seismic reflection survey along two main E-W sections and two S-N sections was carried out by the Dian-Qian-Gui Geophysical Petroleum Inspecting Corporation in 1995. The measured area is identical with the MT profile. The geological interpretation of the seismic reflection results may be summed up as coming under three categories (Figure 3).

1. The strata sequence can be divided into three layers, based on two reflecting boundaries, Tg and Th.

a) The top layer is above the Tg wave group, which corresponds to the Miocene rocks. It has an average velocity in the range of from 1400 m/s to 1800 m/s and has the velocity of reflecting horizon of less than 3000 m/s. The thickness of the Miocene rocks range from 32 m to 643 m.

b) The intermediate layer, which is called the Tg-Th reflection wave group, has been sandwiched between the Tg and Th reflecting boundaries. It is the Precambrian Gaoligongshan group with a thickness of about 2000-3000 m. The average velocity ranges from 3000 m/s to 4800 m/s and the reflecting horizon velocity is more than 4000 m/s.

c) The basement of granite was overlaid by the Th reflecting horizon. The great disturbance of the reflecting wave is due to the granite basement.

2. Many faults in the Miocene, which are difficult to identify in the field, can be identified on a seismic record section. The longitudinal striking fault is the main direction. Secondly, there are latitudinal and north-eastem faults. The great majority have normal fault-plane dips around 60-70' and dip westwards. The fault surface is actually concave upwards at depth and the dip angles change gently. Fault density reaches almost 2 per kilometer.

3. A low velocity zone has been discovered inside the Gaoligongshan group. The horizon velocity of the velocity zone ranges from 3000 to 4290 m/s, which is less than 500-2000 m/s than its top and bottom beds. The depth of the top bed of the zone is variable and is hidden from 1050 m to 1500 m beneath the surface. A low velocity zone could form the reservoir of the Rehai field.

7. CONCEPTUAL MODEL

Despite the fact that much of the recently acquired geothermal data from the Rehai (Hot Sea) field are unpublished, enough geological, geochemical and geophysical data are available to foxmulate a conceptual model of the whole geothermal system. At present, the model is 2-dimensional along the MT and seismic inspecting profile with an E-W direction. As time passes and with new data acquired, this model must be updated and quantified.

The geological and geophysical evidence indicates that the Rehai geothermal field .developed in a late Cenozoic volcanic zone. The geothermal system in the Rehai consists of two separate geothermal regions: the Rehai in a narrow sense, including Liuhuangtang, Zaotanghe, Huangguaqing and Songmu-qing in the eastern region, and the Reshuitang at the western side. The total area of the Rehai field is not yet established as its boundary is still not defined.

From the cross-section of the MT sounding and microearthquake survey - a conductivity zone or a seismic-free zone, which may represent a partial melt, lies at a depth of 7 km. The cooling magma chamber could be a heat source intruded in the Late Pleistocene.

The Miocene stratum is the cap rock of the thermal field due to strong self-sealing by kaolinitization and deposits of silica sinter or travertine. The thickness of the cap rock as a confining bed is about 300 m.

The reservoir of the Rehai field could be constituted by a low velocity layer inside the Precambrian Gaoligon-shan rocks. A low velocity layer is composed of thin permeable zone within the Gaoligongshan gneiss and a zone of secondary permeability near faults.

The thermal fluids from the reservoir at depths of 1250 m indicate a homogeneous body of hot water with a temperature of 200-270°C. The thermal water discharged from neutral boiling springs contains approximately 2800 mg/L of sodium chloride-bicarbonate. The gases discharged from fumaroles and boiling springs are mainly CO_2. Anomalously higher helium isotope ratios are indicative of a fluid supply from mantle and/or deep crustal sources.

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