GEOLOGICAL AND GEOCHEMICAL INTERPRETATION OF HOT SPRINGS AND CARBONATED SPRINGS ALONG THE SOUTHEAST COAST OF CHINA

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ABSTRACT

Based on the distribution of hot springs and carbonated springs already known along the southeast coast of China, this paper deals with the arrangement and origin of these hot springs, and presents a model of "produced heat by deformation of crustal layering." According to data on the chemistry of the springs and calculations on the balance between water and minerals in the geothermal reservoir, the author suggests that certain materials, including the products of mantle origin and metamorphism at depth, may escape into the geothermal systems, and that the regional metamorphism of zeolite facies is developing along the coastal area of southeast China.

INTRODUCTION

In such a broad region of southeast China, about 30 to 20° N latitude and 110 to 120° E longitude, the mean annual groundwater temperature gradually increases from 20°C in the north to 26°C in the south. Under this circumstance the temperature limit determined for hot springs is 25 to 30°C. Exploration of hot-spring areas indicates that the drainage area of a hydrothermal system is normally less than 10 km^2. Therefore, the thermal features appearing within an area of several km are considered as a single site. In this way, hot springs in this region total 577 in number, nearly one fourth of the total springs over the whole territory of China. In fact these hot springs are concentrated in a narrow coastal zone including east Guangdong and south Fujian, which together with Taiwan province constitutes one of the two major geothermal zones in China, the "Taiwan-Guangdong-Fujian high- and moderate-temperature geothermal zone" (Yao, 1979).

A carbonated spring is defined in terms of the dissolved free carbonic acid contained in the water, at least 0.2 gram per liter. This is because the carbonic acid enriched by hypergene activity generally can not reach such a limit and the pH value of the water will always be less than 7.

Since 1982, hydrochemistry has been applied during the regional assessment of geothermal resources of the area, and existing data have been collected on the distribution and chemical composition of all the hot springs and carbonated springs (totaling 40, including 3 boreholes). Among the 24 hot springs with a temperature of over 80° C, 21 were sampled. The pH and carbonate content were analyzed by pH-meter and titration with hydrochloric acid, respectively, in the field. Water-rock balance was calculated with the Icelandic method and program (Arnorsson, Sigurdsson and Svavarsson, 1982).

OUTLINE OF REGIONAL GEOLOGY

There occurs a Proterozoic orogenic cycle, which consists of a set of metamorphic rock series (labeled P) in the northwest of this region (mosaic map Figure 1). Entering the studied area toward the southeast, the Caledonian orogenic cycle can be observed, comprising a set of epimetamorphosed phyllite-slate series, locally nonmetamorphosed, of Sinian and lower Palaeozoic age (labeled C). Still southeastwardly, the region is characterized by extensive occurrences of volcanic rocks and granites of Mesozoic age. Finally along the coast and in Taiwan province basic-ultrabasic and metamorphic rocks of Cenozoic age and active volcanoes (only in Taiwan) can be found. It is obvious that the tectonic activities and rock formations (including granites) become younger and younger from northwest to southeast. The crust grows

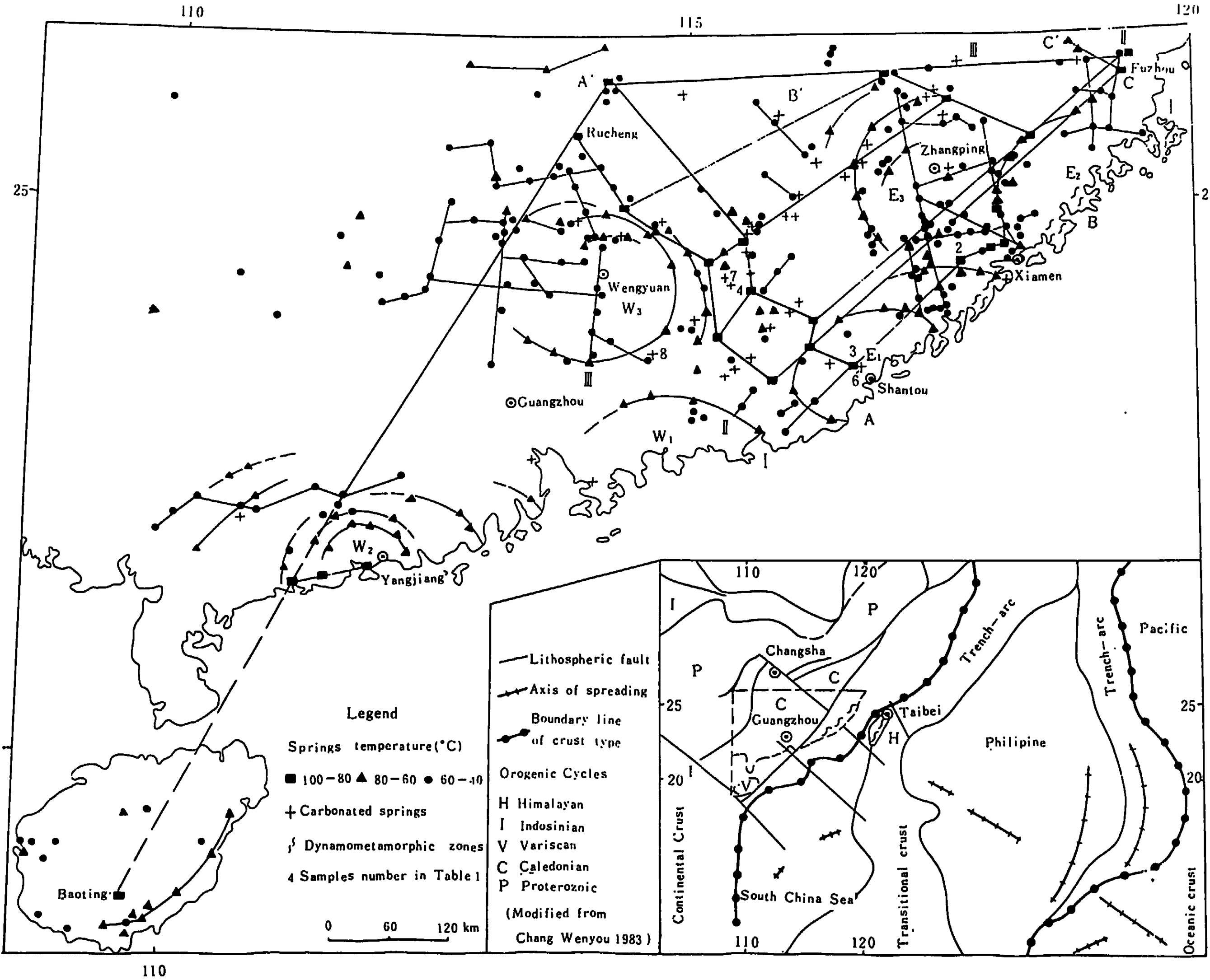

Figure 1. Map showing distribution of hot springs and carbonated springs along the southeast coastal area of China

toward the southeast. The thickness of the crust is 35 km in the northwestern part, 30 km in the coastal area and only 10 to 20 km in the South China Sea. Apart from the above in geological age, there appears to be a tendency since the Mesozoic for more and more intense magmatic activity, metamorphism, crustal movements, and recent earthquake and hot-spring activities, growing stronger in the same direction: from inland towards offshore.

Because of the extensive occurrence of the Yanshanian (Jurassic-Cretaceous) granites and volcanic rocks in the coastal area, 65 percent of the total hot springs issue from granite, 15 percent from neutral-acid volcanic rocks, and the rest from sedimentary rocks. Three hot springs are found to have a temperature near the boiling point: Zhangzhou, Shantou and Yangjiang along the continental margin. Most of the carbonated springs are cold, a few are exceptionally above 60° C. The natural discharge of the hot springs is predominantly 5 to 8 l/sec.

DISTRIBUTION OF HOT SPRINGS AND CARBONATED SPRINGS

The variation of heat flow from place to place within an area of the same lithologic character, of the same geologic unit, can not be appealed to for such remarkable differences in spring temperatures. In many cases, it is impossible to explain this by the varying admixture of shallow cold water or by the heat loss of the ascending hot water. The probably acceptable assumption is that the temperature differences between individual hot springs reflect the different circulation depths of hot waters in fractures and relate to some geological events that took place at different stratification levels in the earth's crust. Therefore, hot springs may be divided according to temperature into four classes: high temperature — 100 to 80° C; moderate temperature — 80 to 60° C; low temperature — 60 to 40° C, and less than 40° C.

All springs are plotted on the map shown in Figure 1. One can see that each of the former three classes has its own geometric arrangement, and the last class of springs less than 40° C is in disorder, which can be neglected. The geometric configuration of springs is of definite geologic significance.

1. Hot springs are concentrated in a network interwoven with lines in a northeast direction: I-I, II-II, III-III and the Yangjiang area, and those in a northwest direction: A-A′, B-B′ and C-C′. The pattern of the spring

Table 1. Composition of representative samples of hot springs and carbonated springs along the southeast coastal area of China (in ppm)

Location & No.	Temp (°C)	pH (25°C)	Li	Na	K	Rb	Cs	Mg	Ca	Fe	F	Cl	SO_4	Total CO_2	Total SiO_2	Total B	Total NH_3	Total H_2S	TDS	^{13}C (PDB,‰)
Hot Springs																				
1. Fuzhou	84	8.97	0.2	128	4.6	0.2	0.0	0.08	11	0.1	11.4	76.5	148	34	93	trac.	0	0.2	524	—
2. Zhangzhou	99	6.61	2.5	2220	120	0.1	1.3	3.3	1288	0.5	2.5	5525	191	46	110	0.26	0.2	0	9670	—
3. Shantou	99	8.33	0.3	364	14.2	0.3	0.0	0.1	17.5	trac.	9.8	510	43	54	110	0.02	0.1	0.1	1140	-6.5
4. Xingning	80	6.62	1.0	304	18.5	0.2	0.0	5.1	67.5	1	6	29.2	268	774	90	0.80	0.03	0	1182	-3.6
5. Baoting	85	8.18	0.1	63	2.2	0.1	0.0	0.1	3.4	0	8.5	6.9	27	86	83	0	0.03	0	274	—
Carbonated Springs																				
6. Shantou	25	6.38	0.2	75	3.0	0.1	0.0	44.4	195	2.4	2.1	45.3	8	1461	80	0	0.04	0	960	-5.8
7. Lizui	33	6.20	—	948	92	—	—	9.2	42.9	1.5	5.1	24.2	45	2752	91	0.39	—	—	2802	-1.3
8. Heyuan-1	55	6.58	0.8	376	18.4	0.3	0.0	5.5	55	1.0	7.7	46.3	139	1157	101	0.29	0.08	0	1290	-4.9
-2	63	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-9.0

***Total** CO_2*, ..., H_2S equal $H_2CO_3 + HCO_3^- + CO_3^{--}$, ..., $H_2S + HS^- = S^{--}$ respectively

network obviously follows that of the distribution of earthquake epicenters found in the historic record of the last thousand years. Those lines of the network are the recent active faults. Both of the fault zones trending northeast (II and III) have been important geologic boundaries since the Mesozoic. Those trending northwest are younger and arranged in equidistance, cutting the former.

2. Moderate-temperature hot springs are arranged in rings. Taking line A-A′ as an axis, one can observe rings W_1, W_2 and W_3 to the west of the axis and E_1, E_2 and E_3 to the east, all of which have a diameter of about 120 km. The centres of the four half-rings in the coastal terrain are all located in the fault zone. In general, around the individual centres of the rings occur the epicenters of strong earthquakes (magnitude 6-8), which have happened since 1067 A.D. (Chen and others, 1984). Each 'hot spring ring' corresponds to the earthquake locality of intensity 7, roughly. The ring-shape configuration of hot springs may not be explained as a ring structure reflected on landsat photographs or geologic maps due to location difference. Since such a phenomenon is closely related to earthquake activities, it is suggested that mass heat energy has been accumulated through multiple strong earthquake events and consequent serious crushing of rocks within the effective range of the hypocenter, forcing the heated fluid to transfer rapidly upward along the fracture system to the surface in the form of hot springs.

3. All the springs within the region are distributed in a sectorial configuration. The framework of the sector is constituted by high-temperature springs. Beyond the sectorial range few hot springs can be found over a large area. The front of the sector is the coast line, which follows the two deep faults, parallel first to the one trending northeast and then to the one trending east-northeast. At the intersection point of the two faults, the northwest Shantou - Rucheng fault belt A-A′ runs nearly parallel to the axis of the sector, where numerous hot springs, mostly high temperature, are concentrated, with the density lessening toward both sides of the axis in alternating belts of dense and sparse distributions. Solution of earthquake focal mechanisms in the region indicates that the regional compressional stress field is also in a sectorial pattern (Lin and others, 1981), the principal axis is in nearly an east-west direction to the east of line II-II into Taiwan island, in a northwest direction along the line from Guangzhou to Yangjiang to the southwest, and in a north-south direction along the line from Zhanjiang to Hainan Island.

The sectorial stress field reflects the collision between the continent and the Philippine and South China Sea plates. At the front of the sector, the temperatures of densely distributed springs are relatively high, with three nearly boiling springs. The number of springs lessens inland. All of the above may reflect the existence of stress and dynamometamorphic zones at the front of the coast during the Mesozoic, as a result of the collision of the plates. As is shown on the mosaic map of Figure 1, the axis of spreading depends on the magnetic field lineation in the sea domain. The Philippine plate is oriented in a northwest direction. In the continental crust to the northwest appears the corresponding lithospheric fault. The Shantou-Rucheng fault belt runs parallel to it in the vicinity. The collision between the continent and the South China Sea plate striking east-northeast may indicate the compression of the continental margin, which is also reflected by the decreasing temperature of the springs round the coastal zone, from Yangjing inland.

In summary, a model of "produced heat by deformation of crustal layering" is put forward to explain the origin of heat and its close relationship with the distribution of geothermal water as follows: high-temperature water originates from the frictional heat of deep fracturing activities; moderate-temperature water absorbs heat produced by interstratal creeping and frictional sliding during the pre-earthquake period, or is supplied by powerful upward heat transmission induced by earthquakes; low-temperature water obtains its heat mainly from the normal geotherm under static pressure. According to the depths of geologic activities related to the heat source of the springs, the earth's crust may be divided into three layers: (1) an influenced layer of deep fracturing activities for long durations, the depth of which is related to the thickness of the crust and others; (2) an earthquake activity layer, at a depth of 5 to 20 km; and (3) effective water-storage layer within various nonactive faults, at a depth of less than 5 km. The nearly uniform distribution of the three individual types of hot springs depends on the space between individual faults and the layering of the deformation-produced heat: high-temperature springs on northwest faults have a space of several ten km; those on northeast faults, 100 to 200 km; moderate-temperature springs, 30 to 50 km; and low-temperature ones less than 10 km.

GEOCHEMISTRY OF HOT SPRINGS AND CARBONATED SPRINGS

Basic chemistry types, characteristics of the alkali component and carbon isotopes of geothermal waters are discussed, and the geochemical process that might be at a depth of several km is inferred.

Basic Chemistry Type of Geothermal Water

Most of the hot springs are the sodium bicarbonate type, less mineralized (TDS about 0.5 gram per liter), pH 7 to 8, with considerable contents of fluorine (5 to 14 mg/1 commonly) and boron (exceptionally high, up to 0.8 mg/1) (Table 1). The hot springs within tens of km from the coast, due to sea water or marine deposits, have a much higher content of total dissolved solids (10 g/l) and belong to the sodium chloride type. However, drilling at many places has revealed less mineralized bicarbonate water at a depth below several hundred m. The sulfate type of water is not common, generally distributed in red beds or limestone formations, but similar variations of water type can be observed as mentioned above. It may be concluded that geothermal water in the region is normally low-mineralized sodium-bicarbonate water, which becomes fresh at some depth. When it flows out of the granite reservoir, it changes chemically as a result of chemical rebalance between fluid and country rocks of another lithologic character.

Oriented Variation in Na/K Ratio of Geothermal Water

A Na/K atomic ratio zoning map shows that: the zoning lines strike northeast, with the ratio being 70 to 90 in the coastal area, 40 to 50 moving inland, and 30 to 40 further to the west of Wengyuan. The Na/K atomic ratio of granitic rocks from the same place, like that of the water samples, has the same trend: 2.0 to 1.4 for the coastal area and 1.4 to 0.65 inland. Potassium variance (K_2O) in Neogene basalt also increases inland, 0.91 percent for the coastal area, 1.7 inland (Sun and Lai, 1980). The alkalic variation of hot springs can be explained in three ways: (1) the statistics show that the alkali content of hot springs is on the whole proportional to the temperature of the springs, while the temperature of the springs in this region has a decreasing trend from coast to inland; therefore, the alkali variation is a result of different solubility under different spring temperatures and reflects indirectly the temperatures; (2) the alkalic variation of the springs reflects the same variation as the country rocks, because the spring water has reached a balance with the country rocks; and (3) alkalic differentiation, developed in the collision belt between plates, exists in recent geothermal systems. It can be concluded from later discussion that the third condition is also true, as are the former two.

Data On Carbon Isotopes of Hot Springs and Carbonated Springs

According to the determination on 17 samples from the hot springs, ^{13}C isotope compositions range from -4 to -9 per mille relative to the PDB standard, which is similar to that in many volcanic areas over the world. It is noticeable that the determination on 15 samples from the Palaeozoic limestone 60 km northeast of Xingning gives the ^{13}C value as positive for 13 of them, the remaining -4 and -9 per mille. It is likely that the carbon contained in spring water is not the product of leaching from rocks but rather from the mantle and metamorphism under high temperature. As Table 1 indicates, carbon isotopic components of both carbonated and hot springs are almost the same, taking Shantou boiling spring and carbonated water as an example. Carbonated springs such as Lizui, Heyuan, etc., are distributed along deep fault zones where Neogene basalts erupted.

Temperature and Chemical Reaction in the Geothermal Reservoir

Chemical geothermometers (silica and cation) are used for the calculation, and give the highest temperature of the reservoirs as less than 150° C. The structure of the temperature field occurs as multicentered. In other words, it is separated into several temperature zones, which can not be linked by uniform and regular isolines. Within each temperature zone, the temperature ranges from 100 to 150° C or to 140° C or 130° C roughly. The characteristics of the temperature field may well verify the heat source model mentioned above. The highest temperature of the geothermal reservoir along the coastal zone of China is 150° C. However, to the east, the highest temperature except for the active volcanic area is 200, 180 and 145° C in the Mesozoic metamorphic Lushan zone at Lushan, Taiwan (Li Dianchang, 1982, lecture). The difference between the former and the latter is quite acceptable and can be explained easily.

Thermodynamic calculations with the program WATCH (Arnorsson and others, 1982) indicate that in general the pH of geothermal fluids in the coastal area is as high as 7.5 to 7.9, except for that which is affected by sea water, and comes down to 6.7 to 7.6 moving inland. All of the reservoirs come to be alkali. The geothermal fluid is normally balanced with quartz and fluorite and oversaturated with calcite, but balanced with feldspar and zeolite for high temperature springs over 90° C. In consideration of the fact that zeolite, as an alteration product, occurs in the drill cores in some geothermal fields in the coastal area, the author holds that a regional metamorphism of zeolite facies is developing in the coastal terrain.

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