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Zhijie Liao

Thermal Springs and Geothermal Energy in the Qinghai-Tibetan Plateau and the Surroundings

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Preface

Geothermal energy is one of the new and alternative energy resources that have not yet rivaled the main energy resources (hydropower, coal, petroleum, natural gas, or even nuclear). Nevertheless, the Earth is a huge heat reservoir with abundant geothermal energy, which has the potential to impact the energy demand of many countries throughout the world. Due to the difficulty in development and the demanding huge investment, the use of geothermal energy has been very slow before the 1970s. The petroleum crisis in early 1970s was one major factor affecting the study and development of the geothermal energy. During that period, many provinces of China began to investigate in large-scale use of geothermal energy and went beyond the balneology of thermal springs. The Geothermal Research Section of Geology Department of Peking University emerged at the time of 1970, when I was fortunate to join this Section. We collaborated with the power system to construct a pilot station of 200 kW using 79 °C hot water. The station has become one of the seven pilot plants on the east of China mainland. But our goals were Larderello, Wairakei and The Geysers. Our Section decided to visit Tengchong volcanic area in Yunnan Province to seek high-temperature geothermal fields from 1973 winter to 1974 spring.

Qinghai-Tibetan (hereinafter called Qingzang) Plateau is a collision zone of continent crust between the Eurasian and Indian plates, where there are many high-temperature areas owing to its unique tectonic setting. How many thermal springs are there in this region? How many high-temperature hydrothermal systems? How high are the temperatures? The answers were unknown before 1970s. To find the answers, the Chinese Academy Science formed Qinghai-Tibetan Plateau Scientific Expedition in 1973, a Geothermal Project Group emerges as that time. Our Geothermal Research Section joined the Expedition in 1975 and became the main force of Geothermal Group.

This book in English is the generalization and summarization of field survey data of Geothermal Project Group of Qinghai-Tibetan Plateau Comprehensive Scientific Expedition of Chinese Academy of Sciences (CAS) from 1973 to 1989. It presents readers rich and various thermal springs distributed over the Qingzang Plateau and its surrounding areas, which are steadily manifesting due to the convergence of the two continental plates. The thermal springs over there are 1684 in total, of which 1380 springs have geochemical data for calculations of temperatures of the reservoirs. The author of this book provides a wealth of data on boiling and hot springs, including their locations, elevations, temperatures, geological data, and the analytical results of water samples, and also tables on warm and tepid springs with low temperatures. The author of this book considers that this research area is the sole high-temperature geothermal belt on Chinese mainland, called Himalayan geothermal belt or Yunnan–Tibetan Geothermal belt. Lastly, this book discusses the relationship between geothermal energy and other energies, and claims that geothermal energy could be an important supplement to the rich hydroelectric resources in the remote southwest China.

The foundation of this book is the following five monographs (in Chinese with English abstract) published over the years by the author of this book and his colleagues.

Wei T, Mingtao Z et al. (1981) Geothermics beneath Xizang (Tibet) Plateau. Science Press, Beijing.

Geothermal Reserch Section of Department of Geology of Peking University (1989) Geothermics in Tengchong, Science Press, Beijing.

Wei T, Mingtao Z compiled, Writers: Guoying G, Zhijie L, Shibin L et al. (1994) Thermal Springs in Hengduan (Traverse) Mountain, Science Press, Beijing.

Zhijie L, Ping Z (1999) Yunnan-Tibet Geothermal Belt—Geothermal Resources and Typical Geothermal Systems, Science Press, Beijing.

Wei T, Zhijie L et al. (2000) Thermal Springs in Tibet, Science Press, Beijing.

These monographs are written based on fieldworks, especially those done by the Geothermal Project Group of Qinghai-Tibet Plateau Comprehensive Scientific Expedition of CAS. This book is the summary and condensation of these monographs. Ever since the Qingzang Expedition ended, during the following over 20 years, the amount of thermal springs in this area has not changed much, but the development of geothermal fields makes a bit headway.

The author of this book thanks our stellar researcher-writers, without whom this book would be a pile of blank pages. The wealth of data in books are taken from field researchers of the Geothermal Group, who overcame plateau reactions and every difficulty. Their outstanding work will always be cherished in my memory. Over the years, the following scientists have participated in the geothermal fieldwork: Wei Tong, Zhifei Zhang, Zhijie Liao, Maozhen You, Meixiang Zhu, Guoying Guo, Minzi Shen, Shibin Liu (the staffs of Geothermal Research Section of Peking University, during 1975–1989), Dexin Wang, Zhiguo Mu and Baoshan Deng (from teacher of Department of Geology and Department of Geography, in 1975 or 1976), Shaonan Dai, Changyi Jiang, Jincai Lu, Fengtong Wang, Xiangmin Wang (in 1975), Baimin Chen, Xiuping Li, Jiapin Tang, Xiaohuan Xi, Shaoping Yang (1976) (more for the high grade students of Department of Geology and Department of Geograph of Peking University), Mingtao Zhang, Changjtn Zhou, Yaxin Zheng (from Commission for Integrated Survey of Natural Resources, CAS), Li Zhu, Shutang Xiao, Shaozhuo Xu, Longlin

Wu, Honglin Song, Xinhua Wang (from Chinese Geology University (Wuhan) during 1973–1974).

Many experts have been working hard in the Plateau for a long time. Though they did not participate in our study tours, they played invaluable roles in the completions of the above monographs. These experts are: Mianping Zheng (from Chinese Academy of Geological Science, Academician of Chinese Academy of Engineering), Dorjee (Academician of Chinese Academy of Engineering), Tingli Liang and others (from Tibet Geothermal Geological Brigade), Dengzhujiacan and others (from Tibet Geothermal Development Company), Fangzhi Wu (from Ministry of Power Industry), Xizhi Jia and Xiyi Jia (from the Second Hydrogeology and Engineering Geology Brigade of Yunnan Geology and Mineral Resources Bureau), Prof. Mei Luo and Prof. Shuyuan Jia (from Chendu GeologY Institute and PLA00933 Troops). They also provided a wealth of information of local thermal springs.

Unfortunate, my colleagues Prof. Wei Tong and Prof. Zhifei Zhang, whose calm guidance in fieldwork and writing made a daunting project possible, and Mr. Shibin Liu, have passed away. Their contributions to Chinese geothermal development would be forever memorized.

Lastly, the author of this book wishes to thank Dr. Yujie Wu, my American friend, who proofread my first draft in English, without his help there would inevitably be many language errors. The author of this book also wishes to thank Ms. Ying Wang and Ms. Haijie Jin, as well as Higher Education Press, for their help to typeset all figures. These works are very difficult for me, an 80 years old man.

Beijing, China Zhijie Liao

The original version of the book was revised: For detailed information please see Erratum. The erratum to the book is available at https://doi.org/10.1007/978-981-10-3485-5_11

Contents

Chapter 1
Classification of Thermal Springs

Abstract This chapter discusses the definition and classification of thermal springs. Based on the boiling temperature of local elevation, the annual mean maximum temperature of the earth and local annual average temperature, thermal springs can be divided into four categories: boiling spring, hot spring, warm spring, and tepid spring.

Keywords Definition of thermal spring · Boiling spring · Hot spring · Warm spring · Tepid spring

One of the largest characteristics of modern active volcanoes is to discharge a large number of thermal springs, which are, however, not limited to the volcanic area. Our ancestors left us large historical documents, where the report of volcanoes was rare, but of thermal springs abundant. These thermal springs reports are far better than those common cold seeps, maybe for the reason that the thermal spring water is hot, and this has the function of disease treatment.

The temperature of thermal springs overflowing on the surface varies dramatically. Some thermal springs give off boiling fog, flying like smoke; some only trickle; some release unbearable stinky smells with the rising heat, while some are so clear, colorless, and tasteless that you can see to the bottom. Despite the differences, thermal springs are all warm groundwater discharged from underneath the ground. But how high the temperature of the groundwater is to count as a thermal spring? And what is the highest temperature that thermal springs at natural emissions can reach? For the first question, the various national standards exist. For example, Germany and Britain's standard says it is higher than 20 °C, while Japanese standard requires it to be higher than 25 °C. Our country's (China's) recent standard sets it to 25 °C. These values are not strictly scientific standard. In fact, as early as 1875 American Gilbert made a scientific definition of thermal spring: A local spring is called a thermal or hot spring if its water temperature is higher than the annual average temperature by 15 °F. In other words, if the temperature of the natural spring water is higher than the annual average temperature of 8.3 °C, then local springs can be counted as thermal springs. This sets the lower

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limit of the temperature of thermal springs. For some countries, topography varies so greatly, that the annual average temperature is different at different regions, and, so the lower limit of the temperature of thermal springs is not the same everywhere. In northern Tibet, the annual average temperature is roughly 0 °C, and so the spring with water temperature only 8–9 °C should be counted as a thermal spring. The annual average temperature in Beijing is 11.6 °C, and so a 20 °C spring can be counted as a thermal spring. In Southern China, Guangdong's annual average temperature is 21 °C, and so the spring water temperature must reach at least 30 °C to be counted as the thermal spring. When a country has a small land area where the terrain change is not dramatic. It can reasonably take a single temperature value as the national standard, but China's territory is huge, and has complex terrain, a united temperature standard for thermal springs is not scientific. As of now with 25 °C being the criterion. A lot of tepid springs (<25 to 10 °C) in the Qingzang Plateau may be excluded from the thermal springs, where as in Guangdong, Hainan and Guangxi, some cold spring (>25 to 30 °C) are counted as thermal springs.

What is the highest degree that the temperature of thermal springs can reach? If you read some information about thermal springs, you will probably see that people have reported varied records. For example, the temperature of the Pingdong thermal spring in Taiwan was as high as 140 °C; the temperature of Big Roll of Liuhuangtang in Tengchong up to 104 °C, and Mt. Tanggula in Tibet has the thermal springs of 100 °C. You may be marveled at these reports, where the temperature of thermal springs is very high! But if you have the basic knowledge of physics, you would think that these reports about the temperature values are wrong. Boiling is basically the gasification phenomenon within liquid, that is to say the water changes from the liquid state into a gas state. Boiling only happens at fixed temperature under a given pressure. This temperature is called the boiling point. The water that reached the boiling point is called saturated water. Under one atmospheric pressure, the boiling point of water is 100 °C. When pressure rises, boiling point will increase and vice versa. On the surface, pressure in each area does not remain the same, as the elevation of a region increases, the atmospheric pressure drops, the boiling point goes lower (Fig. 1.1). In the Tibet Plateau, if the altitude is 4000 m, the boiling point of water is 87.5 °C, when the altitude increased to 5000 m, the boiling point goes down to 85 °C. In the Liuhuangtang of Tengchong County in Yunnan Province, the elevation is 1600 m, and the boiling point is 95 °C. In the conditions where the surface pressure is certain, the water discharged from the underground is saturated water corresponding to the local elevation. Therefore, a thermal spring's temperature is generally not higher than local boiling temperature (Fig. 1.1).

This means that in the Tibet Plateau with its elevation 5000 m, the highest temperature of thermal spring is 85 °C, whereas in the Liuhuangtang of Tengchong with 1600 m elevation, the highest temperature of thermal springs is 95 °C. At these temperatures, thermal springs can be called boiling springs. The discharging of boiling springs is always accompanied by steam around the spring. Such steam is vapor containing saturated water, also known as wet steam. The temperature of wet steam will not exceed the saturation temperature. Someone called boiling spring as

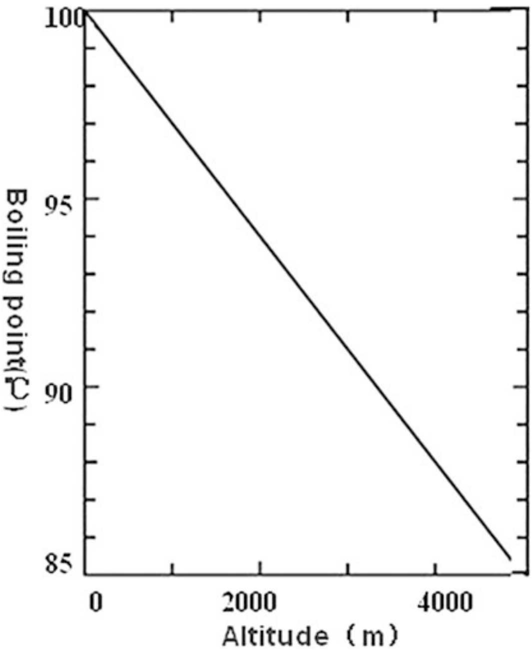

Fig. 1.1 The relation between boiling point and elevation

overheated springs, but that is a misconception. Because the water in boiling spring is not superheated water, but saturated water. Sometimes due to the presence of a large amount of steam, boiling spring temperature may be slightly more than the boiling point, but no more than 1–2 °C. People reported that the hot water temperature in Big Roll Pan of Liuhuangtang in Tengchong Country reaches 104 °C. But that is unbelievable. In 1973, we measured the temperature of Big Roll Pan to be 95 °C, and the temperature of the water 1.5 m deep in a jet of northwest corner of Big Roll Pan to be 96.6 °C, only 1.6 °C higher than the local boiling point. In the same spring area, the measured temperature often varied quite dramatically, the reason is that on the one hand the measuring instrument was alcohol thermometer, which is not very accurate under high temperature; on the other hand, the temperature probe often went deeply down into the internal of springs, the temperature readings thus did not reflect those at the spring outlet. According to the above analysis and investigation, we can say that the minimum temperature of the thermal spring is higher than the annual average temperature of 8 °C. And the highest temperature that a thermal spring can reach should be the boiling point in the local elevation, or at most 1–2 °C higher.

In history, the springs with a temperature higher than the local cold groundwater were called warm springs in China, while in other counties they are called thermal springs. With the advance of science, our understanding of the nature has been gradually deepening and advancing. Therefore, we need to make scientific classification of thermal springs. In the early stage of human history, people's understanding of thermal springs is limited to comparing the spring's temperature with that of the surrounding environment or human's feeling of hotness or coldness. But each individual has a (sometimes very) different sensation of the temperature. For example, some young people are very comfortable to bath in thermal springs at 37 °C, but this temperature would feel quite cold for many senior people. Therefore, the boundaries between warm and hot are not clear and strict.

With the advance of science, people in the field of studying and utilizing thermal springs has noticed three important temperature boundaries: the annual average temperature of the local region, the average annual maximum temperature of the earth (35 °C), and the boiling temperature at the local elevation. When the water is discharged onto the surface of the ground, if its temperature is higher than the annual average temperature of 8 °C and lower than the local earth annual mean maximum temperature of 35 °C, it can be called the tepid springs; if its temperature is higher than 35 °C, and less than 45 °C, it can be called thermal springs or warm springs; The temperature value 45 °C can be used as a boundaries between warm springs and hot springs, because human beings cannot directly bath in a spring where the water temperature is higher than 45 °C. The water of hot spring can be directly sent into people's living facilities or for industrial and agricultural production. The upper limit of hot springs' temperature should be lower than the boiling point of local elevation. If the spring's temperature reached the boiling point, it should be called boiling spring. If boiling spring emits both boiling water and steam, it can be called fumaroles. If there is no spring in an area, but there is steam spurting out from the ground, the area is called steaming ground. Boiling springs, fumaroles, and steaming ground are all high-temperature hydrothermal activity areas with two-phase manifestations, and they often have many impressive geothermal landscapes.

Chapter 2
Thermal Springs in China

Abstract This chapter introduces the quantity and distribution of thermal springs in China, Based on the investigation of whole country in 1970s, the total number of thermal springs of whole nation was 3398, including Taiwan Province 94. The most concentrated region of thermal spring is Yunnan and Tibet in the first, Fujian and Guangdong second. The biggest distribution density is Taiwan. The boiling spring only emerges in Tibet, west Sichuan, Southwest Yunnan, and Taiwan, Qinghai is only one.

Keywords Quantity of thermal spring · Distribution of thermal spring · Concentrated region

How many thermal springs are there in China? Prior to 1970 it is unclear. The most senior Chinese geologist Hongzhao Zhang wrote a booklet "Compilation of Chinese Thermal Springs" in 1956 (Zhang 1956). This booklet records approximately 972 thermal springs. In 1970s, most of the provinces or autonomous regions made geothermal reconnaissance survey. Meanwhile, the Qinghai–Tibet Plateau Comprehensive Scientific Expedition of Chinese Academic of Science (its geothermal group's main members: Geothermal Research Section of Department of Geology of Peking University), and the PLA 00933 Troops in the Qingzang Plateau and Hengduan Mountains (West Sichuan and southwest Yunnan) have done geothermal study, found only in this region the number of thermal springs reached 1600. The estimate of the total thermal springs of whole country could be between 2500 and 3000. The statistical number of thermal spring of whole nation was 3398, including Taiwan Province 94 by Geothermal Professional Committee of China Energy Research Society in 1986.

According to present irrefutable data, the most concentrated region of thermal springs is Yunnan Province and Xizang (Tibet) Autonomous Region in the first place, Guangdong Province and Fujian Province second. But according to density of distribution of thermal springs, Taiwan is first.

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The real number of thermal spring in Tibet is 645, in which Ngari Prefecture has 88, Xigaze 117, Lhasa City 34, Nagqu Prefecture 187, Shangnan Prefecture 44, Nyingchi Prefecture 49 and Qamdo Prefecture 126. From the geological structure, they are mainly distributed in both north and south sides of Yarlung Zangbo suture, from where go northward into the Chang Tang plateau, and southward across the Himalayas, the number of thermal springs immediately reduce. In the Tibetan plateau, the average altitude is over 4000 m, the boiling point is very low, at around 86 °C. Where the annual average temperature is at 0 °C. According to the definition of science, the temperature of spring reaching 8 °C can be called thermal springs at Tibet Plateau, The number of boiling spring (>86 °C) has 48 in Tibet; accounting for 7.5% of the total thermal spring; hot springs (<86 to 45 °C) area has 179, making up 27.8% of the total thermal spring; warm spring(<45 to 35 °C) area is 294, amount to 45.1% of the total thermal spring; tepid spring (<35 to 8 °C) area is 127, accounting for 19.7% of total number of hot springs. Tibet's boiling spring mainly exposed in the vicinity of the Yarlung Zangbo suture, so Xigaze Prefecture is at most, up to 21, followed by Ngari Prefecture, reaching 10, Shangnan Prefecture 7, Lhasa City 6 and each 2 for Nyingchi Prefecture and Nagqu Prefecture. Hot springs of 51 appear in Nagqu Prefecture being the most, Xigaze Prefecture followed for 34, Qamdo Prefecture has 27, Nyingchi Prefecture has 20, Ngari Prefecture 19, Shangnan Prefecture 16, and Lhasa City 12. Warm springs are concentrated in Nagqu Prefecture (98) and Qamdo Prefecture (64), where there is the upstream of the three rivers (Nujiang river, Lancangjia ng river and Jinshajiang river). The springs here account for 55.9% of all warm springs in Tibet Autonomous Region. In addition there are more warm springs. Xigaze (49) and Ngali Prefecture (35). Tepid spring at are mostly found in Nagqu Prefecture (36) and Qamdo Prefecture (35) (Tong et al. 1981, 2000).

Qinghai–Tibet Plateau Comprehensive Scientific Expedition of Chinese Academy of Sciences in Tibet has inspected the 354 thermal springs and samplings and analysis were done from 1973 to 1976. Most of boiling springs found in Tibet discharge sodium chloride type of water that is also boron rich. Some boiling springs discharge Cl–HCO_3–Na type water or HCO_3–Cl–Na type water due to blending of different degrees of cold water. Thermal springs in Tibet are high in salinity regardless the temperature level, however, with the increase in bicarbonate component, their TDS values will decline.

Yunnan Province is the largest province in terms of number of thermal springs in China. The number of springs with temperature >25 °C reached 862 in Yunnan. Among these springs, 20 are boiling springs, 314 hot springs, 208 worm springs, 321 tepid spring. The 20 boiling springs in Yunnan Province all appear in the south Yunnan and the west Yunnan to the southwest of the Red River fault zone, where Lincang City has 6, Baoshan City 4, Dehong Dai and Jingpo Autonomous Prefecture 4, Xishuangbanna Dai Autonomous Prefecture 3, the Puer City, the Dali Bai Autonomous Prefecture and Honghe Hani and Dai Prefecture each 1. In the 20 boiling springs, only Rehai (Hot Sea) Geothermal field of Tengchong County discharges sodium chloride type of water, the rest discharge sodium bicarbonate type of water. But all these high temperature boiling springs have high F content but low B content. For relatively lower temperature hot springs and warm springs, especially tepid springs, their water chemistry type is basically HCO_3–Ca or HCO_3–Mg type. TDS value of Yunnan Springs are very low, Except the Rehai (Hot Sea) geothermal field of Tengchong County is higher than 1 g/L, but all of them are <1 g/L. The rest thermal spring is also no exception. In other words, Yunnan's thermal spring except Tengchong's Rehai Geothermal field, their discharging thermal water all discharge freshwater (Tong et al. 1989, 1994).

The western Sichuan (including Garze Tibetan Autonomous Prefecture, Aba Tibet and Qiang Autonomous Prefecture, Liangshan Yi Autonomous Prefecture and Pangzhihua City), in fact, is the eastern part of Qingzang Plateau, where there are 290 thermal springs. The thermal springs of western Sichuan mainly (70% and high temperature spas) are distributed in Ganzi Tibetan Autonomous Prefecture, which has 205, including 7 boiling springs. Aba Tibetan and Qiang Autonomous Prefecture has only 20 thermal springs, including 14 tepid springs. But there is one boiling spring in Aba County, where altitude is 4500 m and temperature is 85 °C. The chemical type of boiling spring water in western Sichuan mainly is HCO_3–Na type, except Yulinhe of Tardo County, which is Cl–HCO_3–Na type. There are 55 thermal springs in Liangshan Yi Autonomous Prefecture, where the highest temperature is 75 °C in Nanhua County (Tong et al. 1994).

Qinghai Province is located in the northern part of Qingzang Plateau. In total, 52 thermal springs are found in this province (Huang 1993). Among these springs, 4 have temperature >80 °C, 6 at 61–79 °C, 10 at 41–60 °C, and up to 29 at 20–40 °C. The temperature of 9 mineral springs is <20 °C, the temperature of remaining 3 springs is unknown. Among the 4 springs with temperature higher than 80 °C, Reshuigou of Guide County has the highest temperature, reaching 93.5 °C. The most special is a boiling spring located on the east slop of Bouguer Daban peak (6860 m) of Kunlun Mountains. The temperature of this spring is higher than 85 °C, and the boiling water gushed from till before valley glacier tongue. The salinity of this boiling spring's water is very low, thus, it could be steam-heated fresh water.

Southeast coastal provinces are another area of concentrated distribution of thermal springs. Both Guangdong and Fujian provinces take precedence in the number of thermal springs, but Taiwan get ahead in the distribution density of thermal springs.

Guangdong Province has 257 thermal springs (>25), sixteen of which are >80 °C, only making up 6% of the total number of thermal springs. The temperatures of the bulk of thermal springs in Guangdong are between 40 and 80 °C, accounting for 70%. There are no boiling springs in this province. The highest temperature of springs is 97 °C in Hengganzi of Yangjiang County near the seashore (Chen et al. 1994).

Hainan Province has 30 thermal springs, two of which are >80 °C, amounting to 6.7% of the total number. They are Qishenling hot spring (94 °C) in Baoting County and Lanyang Farm (82 °C) in Danzhou City. The temperatures of 25 thermal springs are between 40 and 79 °C, making up 83% of the total number.

Thermal springs (>25 °C) in Fujian Province emerge in 184 sites, eight of which are >80 °C, accounting for 4% of the total. The highest temperature is 89 °C in Nancheng of Dehua County. The temperatures of 70% thermal springs in Fujian are between 40 and 80 °C. And the temperatures of a quarter of thermal springs are less than 40 °C (Zhuang 2010).

The distributions of thermal springs in both Guangdong and Fujian are determined by geological structures, mainly in the intersect point of pressure faults of the North-East trending with the tension fault of the North-West treading. The chemistry type of water in these springs is mainly bicarbonate type, but those at seashore has are sodium chloride type owing to the contamination of sea water.

Taiwan Province has the highest distribution density of thermal spring in China. The number of thermal springs per unit area is up to 35.6. The total number of springs is between 80 and 100. Spring water temperatures fall into the following two intervals 38−70 and 84–99 °C. The boiling springs are mainly located in Taiwan northernmost Datun volcanic area, Guishan Island in Yilan County and the deep fault zones of east side of the Central Mountain Range. The springs of Datun volcanic region discharge sodium chloride–sulfur type of water, while the boiling springs along the deep fault belts discharge sodium bicarbonate type of water (Chen 1989).

Hunan is another province where the number of thermal springs is over 100, reached 138. The spring temperatures are most between 40 and 60 °C. Only two springs have temperatures exceeding 80 °C.

In eastern China, thermal springs are mostly distributed in the provinces: Jiangxi (94), Liaoning (47), Hubei (44) and Hebei (37). This is not a complete list.

The eastern part of China has vast great plains, such as the North China plain, the Northeast plain, Jianghuai plains, and Jianghan plain and Wei-Fen graben, although no springs are exposed on the ground, but there is rich underground hot water. A lot of geothermal wells have been drilled since 1970s, and they can be actually counted as artificial hot springs.

Table 2.1 is the statistics of thermal springs and geothermal wells in municipality (which are directly under the central government), provinces, and autonomous regions (Wen et al. 2010).

Table 2.1 shows that the total of the thermal springs is 3089 in the whole country, Tibet Autonomous Region takes 20.9%. Yunnan Province takes 27.9%, western Sichuan (290) 9.4%, Qinghai Province 1.4%. That is, the thermal springs in Qinghai–Tibet (hereinafter called Qingzang) Plateau and its surrounding account for 60% of the total number of thermal springs. And boiling springs are only found

Table. 2.1 The statistics of thermal springs and geothermal wells

City, Province, Autonm., Region	Num. springs	Area 10^4 km^2	Num./ 10^4 km^2	Num. Wells	City, Province, Autonm., Region	Num. Springs	Area 10^4 km^2	Num./ 10^4 km^2	Num. Wells
Beijing	3	1.7	1.76	300	Tianjin	0	1.2		251
Hebei	25	19	1.32	200	Shanxi	7	16	0.44	220
N.M.G	6	118	0.05	1	Liaoning	36	15	2.4	10
Jilin	6	19	0.32	5	Heilongj.	0	46		18
Jiangsu	5	10	0.5		Shanghai	0			
Zhejiang	6	10	0.6		Anhui	18	14	1.29	
Fujian	172	12	14.33	94	Jiangxi	82	17	4.82	22
Shandong	17	16	1.06	100	Henan	23	17	1.35	300
Hubei	53	19	2.79		Hunan	130	21	6.19	76
Guangdong	282	18	15.67	15	Guangxi	35	24	1.86	10
Hainan	35	3.4	10.29	60	Sichuan*	305	57.2	5.53	3
Guizhou	72	18	4.0	40	Yunnan	862	39	22.10	230
Tibet	645*	123	5.24	60	Shanxi	14	21	0.67	186
Gansu	14	43	0.33	3	Qinghai	44	72	0.61	10
Ningxia	2	6.6	0.32	2	Xinjiang	62	166	0.37	8
Hong Kong	0				Macao	0			
Taiwan	128	3.6	35.56	15	Total	3089			2239

Statistics data in 2010. *Data of Tibetan thermal springs are taken from “Thermal Springs in Tibet” (Tong et al. 2000), and the data* of Sichuan include Chongqing’s data (Wen et al. 2010; Liao 2012)

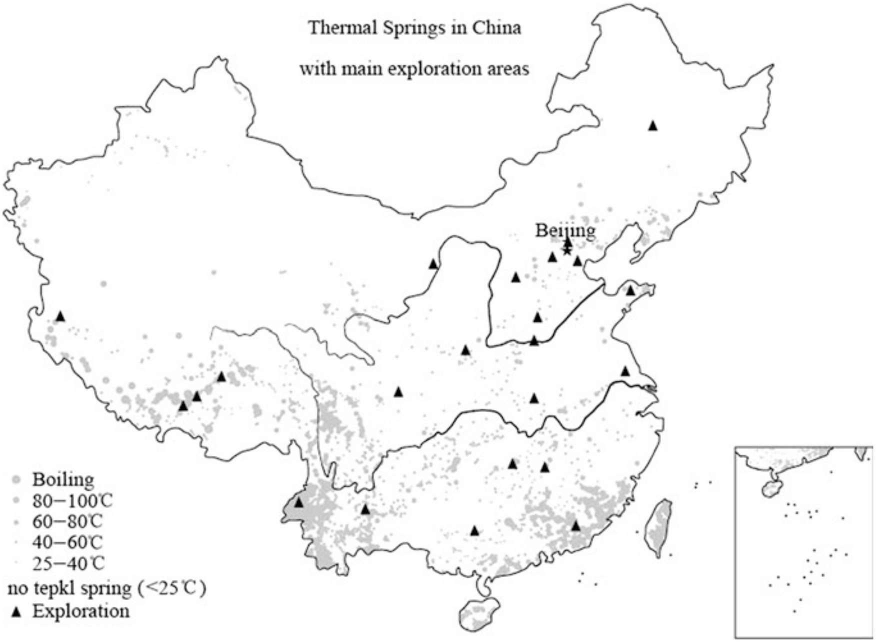

Fig. 2.1 The distribution of thermal springs in China (after Tian et al. 2006; with a bit of alteration)

in this area. Chinese southeast region has higher density of the thermal springs, Guangdong takes 9.1%, Fujian 5.56%, Hunan 4.2%, and Taiwan 4.15%, and Jiangxi 2.7%, and the sum over all these provinces is 25.7%. The remaining 24 provinces and autonomous regions account for only 14% (Fig. 2.1).

References

Chen ZX (1989) Thermal spring and geothermics in Taiwan. Geology 2:327–340

Chen MX, Wang JY, Deng X et al (1994) Geothermal resources in China—formation characteristics and potential evaluation. Science Press, Beijing (in Chinese with English abstract)

Huang SY (1993) Hot spring resources in China—explanation of the distribution map of hot spring in China (1: 600,000). China Cartographic Publishing House, Beijing (in Chinese with detailed English abstract)

Liao ZJ (2012) Volcanoes, thermal springs and geothermal energy in China. China's International Broadcasting Publishing House, Beijing (in Chinese)

Tian TS, Li ML, Bai Z (2006) Chinese geothermal resources and development and utilization. Chinese Environmental Sciences Press, Beijing (in Chinese)

Tong W, Zhang MT (eds) (1989) Geothermics in Tengchong. Science Press, Beijing (in Chinese)

Tong W, Zhang MT (eds) (1994) Thermal springs in Hengduan (Traverse) mountains. Science Press, Beijing (in Chinese with English abstract)

Tong W, Zhang MT, Zhang ZF, Liao ZJ et al (1981) Geothermals beneath Xizang (Tibetan) plateau. Science Press, Beijing (in Chinese)

Tong W, Liao ZJ, Liu SB et al (2000) Thermal springs in Tibet. Science Press, Beijing (in Chinese)

Wen DG, Zhang LZ, Sun XM et al (2010) Administrative information system for geothermal resources in China. Geological Publishing House, Beijing (in Chinese)

Zhang HZ (1956) Compilation of Chinese thermal springs. Geological Publishing House, Beijing (in Chinese)

Zhuang QX (2010) Research and practice of geothermal in Fujian. Geological Publishing House, Beijing (in Chinese)

Chapter 3
Geological Setting

Abstract This chapter analyses the geological setting of appearance of thermal springs in different provinces in China. High-temperature geothermal regions emerge on the margin of plate tectonic. Qinghai–Tibetan Plateau is a collision of continental crusts between Eurasian and Indian Plates. Taiwan is located in the Pacific Ring of Fire. Fujian and Guangdong are closed the margin of east edge of Eurasian Plate, but is not on the island arc of west pacific ocean, where is a shovel-like fracture system dip to east and short of boiling springs.

Keywords Geological setting · Collision belt of continental crusts · Island arc · Shovel-like fracture

In China, the Qingzang Plateau and its surrounding areas for about 2.5 M km^2 have 60% of the total of thermal springs, and the southeast coast for about 0.54 M km^2 distributed 23% of the total of thermal springs, while the remaining 6.6 M km^2 distributed only 17% of the total of thermal springs. Such a pattern is obviously affected by China's geological structure.

According to the theory of plate tectonics, China is located in the southeast edge of the Eurasian Plate. Adjacent to the east side of Chinese mainland is the Philippine Micro Plate of the Pacific Plate and the southern part of Qingzang Plateau is a collision zone between the Indian Plate and Eurasian Plate. Logically it should appear two high-temperature geothermal belts to the southeast and southwest of China. But, the reality is not so.

Qingzang Plateau is a continental crust–continental crust collision zone, its development has gone through a long process. The beginning of the Eocene epoch, which is between 60 and 45 Ma, is the "soft collision" period, during which the northern oceanic crust of the Indian plate subduct to underneath the Eurasian plate, and its northward drift velocity then dropped from 17 cm/a down to 10 cm/a. After 45 Ma, the Indian plate began to migrate northward. And this is the "hard collision" phase, and the speed was further down to 6 cm/a. The oceanic crust of northern part of the Indian plate slowly disappears in the process (Lee and Lawver 1995; Aitchison and Davis 2001).

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During the late Paleogene epoch (about 37–30 Ma), the collision of continental crusts between the Indian and Eurasian Plates occurred, forming the Yarlung Zangbo Collision Zone and making the oceanic crust disappear. Further convergence in the Neogene led to the development of the Himalayan Thrust Zone to the south, with shortening in a "thin-skinned" tectonic system. There are three major thrusts from south to north: the Main Boundary Thrust (MBT), or the Main Central Thrust (MCT) or Main Himalaya Thrust (MHT), and the Main North Thrust (MNT) or Kangmar Thrust (KT). The Main Boundary Thrust and the Main Central Thrust appear to the south of the watershed of the Himalayan Mountain in Nepal, Bhutan and India (Tapponnier et al. 1981; Allegre et al. 1984; Wan 2004).

The main thrust planes of Himalayan Thrust Zone all dip to the north at low or intermediate angles. With the hanging wall over thrust toward the south, the thrusting took place between 23.5 and 16.8 Ma during the early Himalayan orogenic period.

Based on the results of INDEPTH project, the deep seismic profiling across the Main Himalayan Thrust Zone makes it clear that the footwall of the thrust zone has been subducted northwards for more than 200 km, reaching a depth of 15 km. At the deepest level the fault plane dips to the north at only 5°, and the depth of Mohorovicic Discontinuity is around 23 km, and a zone of partial melting is recognized beneath the Yarlung Zangbo Suture, where the thickness of crust increases to 60–74 km (Zeng et al. 1995; Zhao et al. 1997; Teng et al. 2003).

Deformation in the Himalayan Stage (23–0.78 Ma) produced a large-scale, thin-skinned thrust zone in western China. The western margin of this system is formed by the Altun sinistral strike-slip fault and the eastern margin lies in the Daxueshan–Xiaojiang Foothills, along a dextral strike-slip and a normal fault zone. Within this area a series of WNW trending fault form imbricate thrust system, such as the Bangongco-Nujiang thrust, the Kongela-Wenquan-Tanggula thrust, the Jinshajiang-Honghe thrust, the Central Kunlun thrust, up to the northern margin of the North Qilianshan thrust. This thin-skinned tectonic system, with a displacement of ten to hundreds of kilometers, was developed mainly in the upper crust, with a major detachment at a depth of 30 km along the low velocity layer in the low crust (Fig. 3.1) (Burchfied et al. 1989, 1992; Royden and Burchfied 1997).

The Qingzang thin-skinned tectonic system developed in the tectonic stress field was caused by the northeastwards subduction and compression by the Indian Plate, making use of preexisting faults.

The deformation of the Qingzang Plateau was three dimensional. There was a large-scale shortening from the end of the Neogene epoch, and in the Early Pleistocene epoch there was vertical thickening, with uplift of the ground surface and E-W extension, especially during the past 3 Ma (Ma et al. 1998).

Crustal shortening was accompanied magmatism: there was intraplate potassium-rich volcanic rocks and muscovite granites formed by crustal remelting, which gives isotopic ages younger than 20 Ma (BGMRXAR 1993).

In the Qingzang Plateau, as a result of main compressive stress with the north-south trending appeared, the E-W extension of Tibetan crust began and many

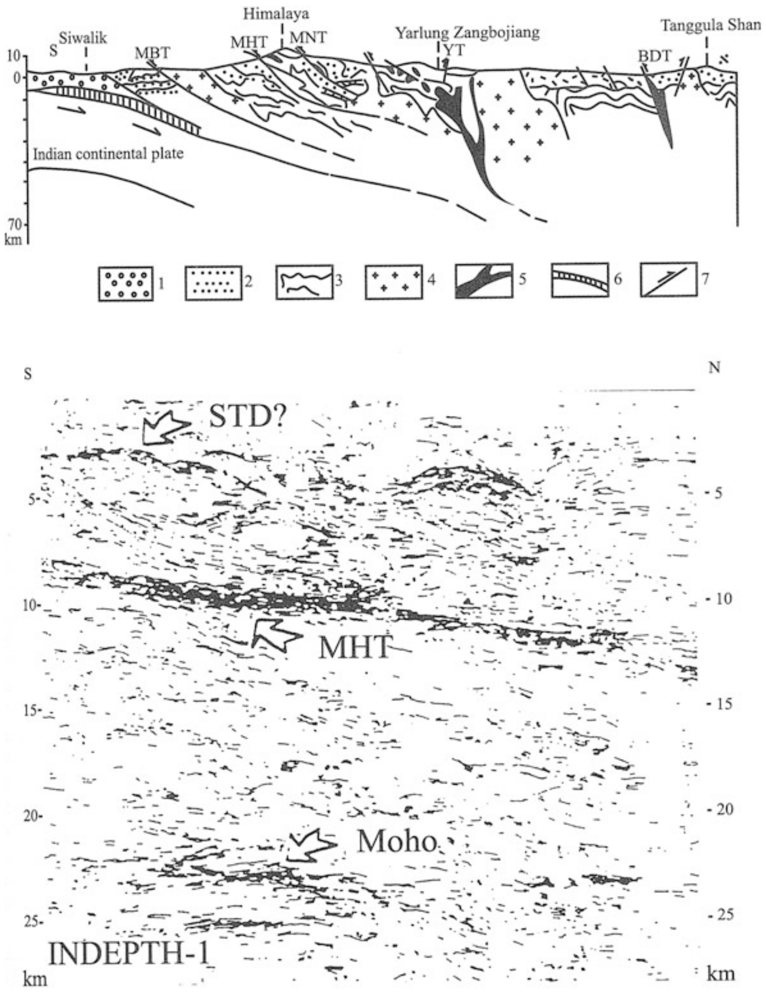

Fig. 3.1 Geological section and INDEPTH seismic profile across the Himalayan Collision Zone (after Zhao et al. 1993, 1997; Wan 2004). **Upper section**: *1* Cenozoic molasse formation; *2* sedimentary cover; *3* crystalline basement; *4* granite; *5* ultra-mafic rocks; *6* subduction zone; *7* thrust zone; *MBT* main boundary thrust; *MHT* main Himalayan thrust; *MNT* main northern thrust; *YT* Yarlun Zangbo fault zone; *BDT* Bangonghu-Dengqen thrust. **Lower Section**: *MHT* main Himalayan thrust; *Moho* mohorovicic siscontinuity, *STD* south Tibet detachment (Zhao et al. 1993, 1997)

north-south grabens took shape in the Neogene. The molten material intruded upwardly into some places of graben and its surrounding, which became the heat source of some high-temperature hydrothermal systems in the vicinity of the Yarlung Zangbo Suture. Most of these high-temperature hydrothermal systems are located in the N-S graben (Fig. 3.2).

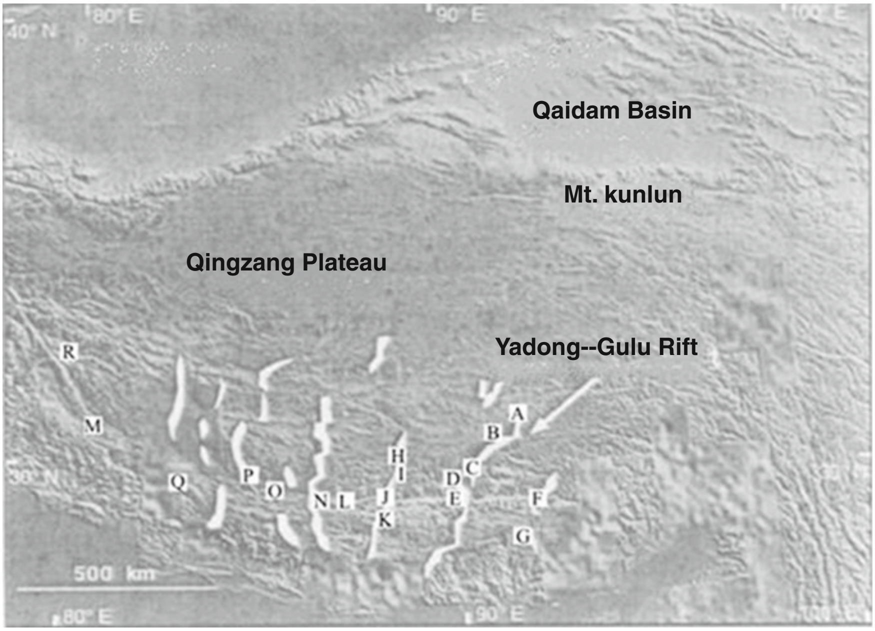

Fig. 3.2 Main rifts of Neogene-Pleistocene in Qingzang Plateau (Zhao and Zhang 2002) and main geothermal areas. *A* Golug; *B* Qucain; *C* Yangbajain; *D* Yangyi; *E* Xumai; *F* Chabmaise; *G* Gobdu; *H* Capu; *I* Qangbugqabka; *J* Lhawangze; *K* Kawu; *L* Buloba; *N* Samig; *O* Daggyai; *P* Ruggog; *Q* Qucain Lungba; *M* Sogdoi; *R* Largju

Due to the mosaic, collision, and subduction between the Indian plate and Eurasian plates, southern Tibet has experienced a very complex tectonic evolution, especially the subduction of Indian plate are still undergoing. Heat flow measurements have discovered that: the fluctuations of heat flow value in the south of the Yarlung Zangbo suture (Himalayan Tethys belt) are between 66 and 106 mW/m^2, in the north of the suture (Gangdise belt) are between 106 and 364 mW/m^2. That indicates the differences between the two thermo-physical mechanisms. The former is the result of heating of tectonic movement, while the latter is that the heat background of tectonic superimposed effect of partial melting or semi-molten magma chambers. At Gangdise belt, the researchers of INDEPTH found many deep reflection highlights in the depth of 15 km, which could belong to the crust remelting type of magma source region. And they also found locally pear-shaped shallow high-conductor in the depth of more than 10 km, which could be molten or semi-molten state magma chamber of late tectonic intrusion. The magmatism at continental crust–continent crustal collision zone is a special type, which is different from island arc and also from the hot and expansion centers. It should be relatively small size and new type.

Although east China is located in eastern edge of the Eurasian plate, but the Chinese mainland is not in direct contact with the Pacific Plate. In the northeast China, the edge of the Eurasian plate is the Japanese island arc. The gap between the Japanese island arc and Asia mainland is Japan Sea. In the central China, the Pacific Plate is adjacent to the Ryukyu island arc, in the west of which is the East China Sea basin. In the southern China, South China Sea basin is between Hainan Province and Philippines. These marginal seas have been interpreted as back-arc basins, forming part of the western Pacific trench-arc-basin system (Uyeda 1977). In this model, all the components of the parallel trench-arc-basin system were formed at the same time. In fact, they are not the product of the same period, the Japan-Ryukyu–Taiwan–Philippine island arc-trench system was formed at a latter epoch in the Paleogene Period (40–30 Ma), the rifting of Japan Sea was in late Miocene and the expansion of the South China Sea was in the Oligocene (32–20 Ma). Therefore, there is no relationship between the expansion of the Japan Sea and the South China Sea and the formation mechanism of the arc-trench system (Wan 2004).

Japanese island arc, Ryukyu arc (the Taipei area is at its western end), and Luzon arc have a strong geothermal activities, which are closely related to a strong volcanic activities and magmatic activities. Therefore, it is not surprising that the Japanese archipelago, the Philippines, Indonesia, and Taiwan of China are rich in high-temperature geothermal resources.

In the east of China mainland, a great number of thermal springs emerge in Guangdong and Fujian provinces. Both their temperature and the flow rates are high. But high-temperature hydrothermal system with magmatic heat source has not been found. This is also determined by the local geological structure. Taiwan is the connection point between the Ryukyu and Luzon arcs. Taiwan is also the contact belt of the Eurasian Plate and the Philippine Sea plate (Fig. 3.3). Philippine Sea plate is a small plate on the west side of the huge Pacific plate. Hall and Blundell (1995) pointed out that during the Neogene epoch the Philippine Sea Plate moved northwards at a rate of 8 cm/a. From 30 to 15 Ma the eastern basin extended E-W at a rate of 2.8 cm/year, to form the Shikoka and Parece Basins, to the south of the Japanese Islands. In the late Neogene and the Early Pleistocene (4–2 Ma), the Philippine Sea Plate was subducted to the north along the Ryukyu Trench and the Nankai Trough, at a rate of 4 cm/year. Taking Taiwan's Hualien as a boundary, on its north, the Philippine Sea Plate with 45° dip angle to the northwest along the Ryukyu Trench subducted below the Ryukyu island arc during the period from the late Neogene to Pleistocene (4–2 Ma), when the submerged depth of slab reached 150 km, the volcanoes appear above the arc, such as Okinawa, Datun, Keelung, and so on. In the south of Taiwan's Taidong, there is an eastward tilt Benioff zone with dip angle of 55°–60°, between 21°N and 22°N, the submerged depth reached 180 km, and it became shallow northwards; at 23°N the Benioff zone disappears.

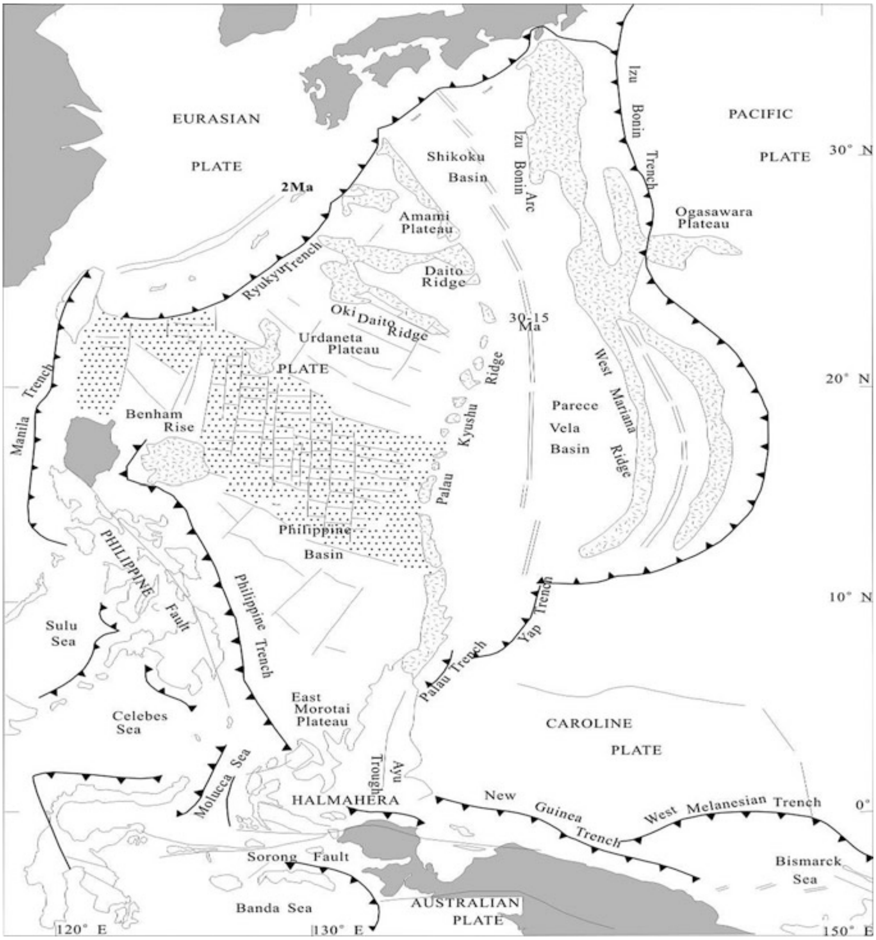

Fig. 3.3 Geotectonic between the eastern edge of Eurasian Plate and Philippine Plate (Hall and Blundell 1995)

At the south of Taiwan, the Eurasian plate along with the early Cenozoic opened Southern China Sea Basin from Manila Trench subducted beneath the Philippine Sea Plate. The andesite at Green Island, and Orchid Island is a northward extension of the Luzon volcanic arc, but they was extruded at Neogene age older than Luzon Islands volcanic rocks. Thus convergent is from north to south development. In the Neogene, between 14 and 2.6 Ma, the west Philippine–Batan–Babuyan—East Taiwan longitudinal valley fault zone changed to a normal fault with sinistral strick-slip, which is the boundary between Eurasian Plate and Philippine Sea Plate. The Taiwan Island suffers strong squeeze from the Philippine Sea Plate westwards,