ScienceDirect

Natural Gas Industry B
Volume 11, Issue 1, February 2024, Pages 6-18

Research Article

Geothermal resource distribution and prospects for development and utilization in China

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https://doi.org/10.1016/j.ngib.2024.01.001
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Abstract

China is tectonically composed of a series of plates and orogenic belts and has been influenced by the Pacific and Indian plates since the Late Paleozoic, forming a regular distribution of Mesozoic and Cenozoic granites. As an important source of geothermal energy, granite is the five elements of geothermal enrichment:geothermal sources; geothermal reservoirs; heat transmission; heat caprock; and heat preservation and it is possible to classify the types of geothermal resources in China according to their distribution in combination with neotectonic movements. China's geothermal energy can be divided into hydrothermal and hot dry rock types in basins and orogenic belts, respectively. Geothermal resources can be divided into hydrothermal, rock, magma, and hybrid geothermal types according to the heat carrier type. Basin geothermal resources are dominated by hydrothermal types, while geothermal energy in orogenic belts with granite includes both hydrothermal and hot dry rock types. Geothermal resources in China can be divided into 6 distinct geothermal regions and 13 subregions, of which the Southwest and Southeast China regions and the Qaidam-Qilian and Jiaoliao subregions in North China with Mesozoic and Cenozoic granites are the most favorable areas for high-temperature hydrothermal and hot dry rock sources. China has complex geological conditions, diverse types of geothermal resources, and broad prospects for development and utilization. Having performed extensive shallow hydrothermal geothermal development and utilization and completed various power generation tests, China's geothermal development and utilization is in a critical stage of transition from the direct utilization of shallow hydrothermal resources to high-temperature geothermal or hot dry rock power generation in middle and deep layers. Basic theoretical research, key technology breakthroughs, and policy incentives are the main issues that need to be addressed in the geothermal industry.

Previous

Next

Keywords

Geothermal resources; Formation conditions; Distribution; Favorable direction; Development prospect

1. Introduction

China is rich in geothermal resources and has a long history of geothermal development and utilization [1,2]. Large-scale geothermal development and utilization began in the 1970s, when seven medium–low-temperature, and one high-temperature, geothermal power stations were built. Afterward, power generation using geothermal energy came to a standstill [3,4]. In 2010, geothermal power generation once again began to attract attention and the medium–deep high-temperature hot water and hot dry rock sources gradually became better known. Hot dry rocks have been found in the Gonghe Basin in Qinghai Province (3705 m, 236 °C; 2017) [5] and in the Juxian, Wulian, and Wendeng counties [6] in Shandong Province,as well as in other provinces. Focusing primarily on medium and shallow geothermal water, China's geothermal development and utilization aregenerally used in health, cultural tourism, heating, cooling, planting, and breeding. Industrial technologies have formed for geothermal utilization such as power generation (Dang-xiong County, Xizang); heating (e.g., Beijing, Tianjin, Xi'an, and Xiong'an); health and cultural tourism (e.g., Southwest and Southeastern China); and ground source heat pump temperature regulation, planting, and breeding (Northern China and other areas). China's direct geothermal utilization technology ranks first in the world; however, its utilization of this power generation is not matched and other indirect utilization technologies arepoorly developed [7].

To systematically understand the geothermal resources and source distribution in China, we discuss the regional distribution of geothermal energy and the prospect of geothermal development and utilization based on the regional geological background, primarily with respect to the geothermal geological conditions, such as the geothermal sources, to promote the rapid development of China's geothermal industry.

2. Geological background of geothermal resource formation in China

2.1. Paleozoic merging of the blocks south of the Siberian Plate and the geothermal conditions in Northwest China

China is tectonically composed of a series of plates and orogenic belts that form basin areas and uplifted areas or fold belts; these include the Yangtze, North China, and Tarim plates and the Xizang-Yunnan, Central China, Tianshan-Xingmeng, South China, and West Pacific orogenic belts.

The Hercynian movement, which occurred in the Late Paleozoic, caused the Tuva-Mongolia, middle Mongolia-Erguna, Yining, Xilinhot, Bureya, Jiamus, Songnen, and other landmasses at the southern edge of the Siberian Plate to be compressed, dived, and merged, resulting in a relatively stable and unified geologic body constituted by the landmasses that arc protrude to the south (Fig. 1). From the Mesozoic to the Cenozoic, both the Pacific and Indian ocean plates expanded northward, squeezing the plates in China northwestward, respectively, forming a southward arc orogenic belt starting from the Altaishan and Tianshan mountains in northwestern China, passing through the Yinshan mountains in central China, and reaching the Xilamulun river in northeastern China.

Fig. 1. Geothermal geological framework map of China.

Paleozoic granite bodies primarily developed in Northwest China, and the tectonic movement manifested itself as a cold tectonic movement primarily characterized by reverse thrusting and overturning, with a generally low heat flow and low temperature gradient in the basins, which are called cold basinsin contrast with the hot basins in eastern China. In terms of geography and climate, Northwest China lacks rainfall and its surface water system is under developed. Surface hot springs are rarely exposed and primarily consist of medium–low-temperature springs with temperatures below 60°C. The conventional regional geothermal conditions are relatively poor. In some areas, relatively new era granite bodies provide a good geothermal source background and form favorable geothermal conditions, such as the development of Triassic granite bodies in the periphery of the Qaidam Basin, especially in its southeastern outer margin. In the Qinling and Yinshan mountain regions, Triassic, Jurassic, and Cretaceous granite bodies have developed sequentially from west to east. Jurassic granite bodies have developed in some areas such as Yanshan and the southern section of the Daxing'anling mountains.

2.2. Mesozoic spreading of the Pacific Plate and geothermal conditions in Eastern China

At the beginning of the Mesozoic, the Yangtze, North China, and Tarim plates merged to form a unified continental landmass. The northwestward expansion of the Pacific Plate pushed the Kula Plate to move in the north-northwest (NNW) direction and eventually subduct under the Eurasian Plate, forming back-arc basins and mountain systems at the southeast margin of the continental landmass, which had an important influence on the geothermal conditions in the area east of the Daxing'anling, Taihangshan, Wulingshan mountains. The northwest (NW)–NNW subduction of the Pacific Plate has had markedly different effects on the North China and Yangtze plates [8,9].

The North China and Northeast China plates are in the distal region of the back edge of the Japan island arc, which belongs to the back-arc tensional fault zone, and regional subsidence is a basic feature of this region [10]. Across the central orogenic belt, namely the Kunlunshan, Qinling, Funiushan, Tongbaishan, Dabieshan, Wulianshan, and Kunyushan Mountains, North and Northeastern China developed primarily large-scale Meso-Cenozoic back arc extensional fault basins with regional crustal thinning, magma upwelling, tectonic arching, tensile faulting, regional subsidence, and cooling depressions, which formed large-scale basins such as the Mesozoic Songliao Basin and the Cenozoic Bohai Bay Basin, as well as small- and medium-sized basins such as the southern North China Basin and the northern Jiangsu Basin [11,12]. The long-distance extension of the northeast (NE)–north-northeast (NNE)-oriented fault controlled the graded distribution of the basins, and the magma upwelling and tensional faulting activities led to an increase in the heat flow, and formed the normal geothermal heat unique to these basins. From the end of the Paleogene onward, the Mesozoic and Cenozoic basins were covered by Neogene and Quaternary systems, which were continuously distributed over a large area and formed the plains of Songliao, North China, and Huanghuai [13]. The outer edges of the basins or plains are very different, and varying degrees of multi-age mixed and multi-lithology coexisting rock masses dominated by acidic magma and the sporadic distribution of volcanic craters or crater groups with rapidly changing geothermal gradients developed.

The Yangtze Plate, located in the southern region of China, is close to the subduction front of the Pacific and experienced strong acidic magmatic activity during the Mesozoic [14]. Along the southeast coast of China, there are a series of rock bodies, faults, and folds extending in the NE–NNE direction. These rock masses are primarily composed of Jurassic granite and are continuously distributed on a large scale with pre-Mesozoic stratigraphic folds and small Mesozoic or Cenozoic clastic basins and volcanic clastic basins. The faults are primarily compression–shear and exhibit fish scale–shape characteristics. From the southeastern coastal area to the Sichuan Basin, the overall tectonic patterns and fault directions do not change significantly; however, the age of the strata become gradually older, the folds tend to be more relaxed, and the magmatic activity and distribution weaken and terminate on a line along Shishou, Yuanjiang, Hongjiang, Jingzhou,and Hechi. This trend indicates that the heat flow gradually decreases from the southeast to the northwest, forming a region of anomalous geothermal heat centered around the southeast coast; that is, a fast-changing and highly anomalous geothermal heat flow relative to that in the basins.

2.3. Cenozoic spreading of the Indian Ocean plate and geological conditions of geothermal formation in Southwest China

During the Cretaceous period, the Indian Plate formed and rapidly drifted northward under the background of the Indian Ocean plate expansion; it then strongly collided and subducted under the Eurasian Plate during the Eocene period. The Himalayan region was uplifted, and a suture zone was formed along the Himalayan-YarlungZangbo River on the southern side of Xizang; this zone controlled the geothermal geologic conditions in southern Xizang, western Sichuan, and western Yunnan, each of which has unusually active geothermal geologic conditions with different characteristics [15,16].

The southern Xizang region is the main part of the collision suture zone between the Indian and Eurasian plates, and the main features of the suture zone in the southern Xizang region are an extrusion fault with a north-northwest (NWW) strike, a granite body controlled by faults, and abnormally high-temperature surface springs [17,18]. The NWW-trending faults with nearly parallel extensions have large distances, long extensions, and small spacing,and control the complicated topographic changes. The NW–northeast (NE)-oriented faults have short extensions and rapidly change, producing an irregular cutting effect on the NWW-oriented faults. The distribution of Jurassic, Cretaceous, and Paleocene granites is constrained by the NNW–NW-trending reverse faults, and the ages of the granites gradually become younger in the southwestward direction [19]. High-temperature springs developed parallel to the regional tectonics under the constraints of the faults and granite bodies.

Southeast Xizang and its eastern region are not directly affected by the northward compression of the Indian Plate, in which the passive drag effect causes the NWW extrusion faults to transform gradually into NW, NNW, and near north–south (NS) strike-slip faults. In the areas west of the Ganzi, Litang, Shangri La, Lijiang, Dali, and Gejiu frontline, the Nujiang, Lancangjiang, and Jinshajiang rivers form the “Three Rivers” or Sanjiang tectonic belt, where the strike slip faults in the north–south direction that form the basic pattern of the structure resulted in deep cutting, complex landforms, and surface water systems. From Shangri La to the south, the north–south fault gradually transformed into the southwest-extending Gaoligong fault and the southeast-extending Honghe fault, limiting the middle and southern sections of the Sanjiang tectonic belt to a trumpet-shaped fault system. In this area, the magmatic activity has significantly weakened and the lithology becomes increasingly complex with younger ages. Hot springs are widely distributed and are controlled by faults and granite bodies, the tempreatures of which change rapidly and gradually increase westward.

3. Geothermal resource formation conditions and types

3.1. Conditions for the formation of geothermal resources

Geothermal resources can be understood as the development of economically or technically exploitable higher temperatures in the shallow crust near the surface, and their heat carriers can be underground fluids (formation water) or rocks, corresponding to hydrothermal or hot dry rock types, respectively. Geothermal resources form when the burial depth of the heat-carrying medium is small and the temperature is high or when the formation temperature reaches an economically exploitable critical point. The formation of economically exploitable geothermal resources requires specific geological conditions, which can be summarized as geothermal sources, geothermal reservoirs, heat transmission, heat caprock, and heat preservation (i.e., SRTCP) excludes water in hydrothermal geothermal energy (Fig.2).

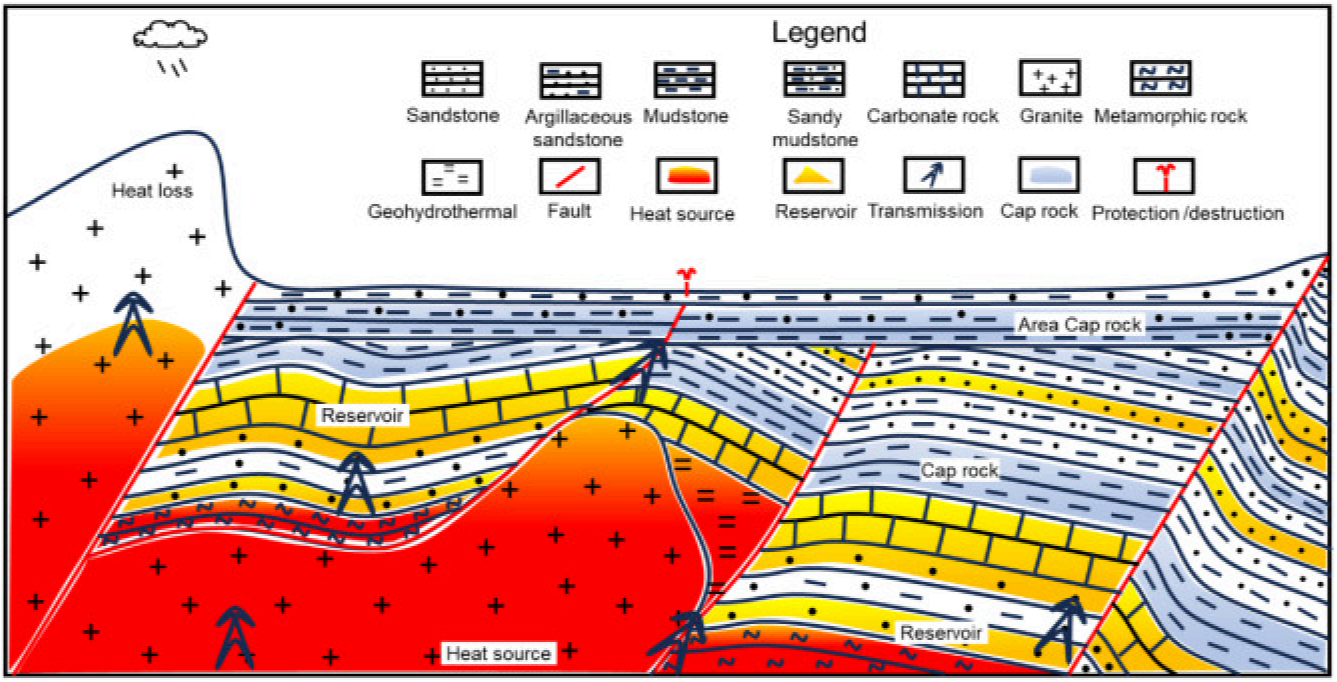

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Fig.2. Schematic diagram of the formation conditions of geothermal resources.

Although there are various types of geothermal sources, the most effective geothermal sources are still the granite bodies intruded during the Mesozoic and Cenozoic eras and their associated gneiss, which contain radioactive elements that release additional heat during the decay process, providing the most common source of thermal energy for the formation of abnormal geothermal resources and an additional geothermal gradient. Metamorphic rocks (gneiss, etc.) also have the ability to generate heat due to the presence of radioactive elements, but the focus is not discussed due to the limited distribution. Shallow buried lava bodies or magma sacs can also provide direct geothermal sources for strata, and deep faults are prone to transporting high-temperature geological fluids to the shallow upper crust.

Hydrothermal and hot dry rock types have different requirements for geothermal reservoirs; in the former, the development of pores, caves, and fractures can store high-temperature hot water, while the latter requires tight lithology and good thermal conductivity to store additional thermal energy. For both types,it is better to be located close to or on top of a geothermal source.

The heat transmission of geothermal energy is primarily realized via heat convection and heat conduction, corresponding to hydrothermal and hot dry rock type geothermal resources, respectively. A connection between the geothermal source bodies and reservoirs is necessary for the formation of efficient hydrothermal energy, and an efficient contact between geothermal source bodies and tight rocks is necessary for the formation of hot dry rocks.

A granite body acts as both a geothermal source body and a thermal conduction and heat dissipation body. Faults can not only transport hot fluids from deep to shallow regions but also allow cold water from shallow strata to enter deep strata. Overlying low-permeability sedimentary cover layers help maintain the reservoir heat, and weak structural changes and lower amounts of fault development reduce the reservoir heat losses, maintaining the original high temperature of the formation as much as possible.

Uplift, denudation, fractures, and changesin the groundwater conditions caused by tectonic movements can easily have a destructive effect on the formed geothermal energy. Factors such as water sources and water cycles, climate, terrain, and faults control the type and scale of hydrothermal energy, while factors such as the age, burial depth, and scale of acidic intrusions and gneiss constrain the economic effectiveness of hot dry rocks.

3.2. Types of geothermal resources in China

Geothermal resources have various levels of performance, each with its own characteristics. According to the type of heat carrier, geothermal energy can be divided into hydrothermal, rock-type geothermal, magma geothermal, and hybrid geothermal (Table 1). Hydrothermal geothermal energy is the most widely distributed type, and springs of different temperatures are often formed in uplifted or folded areas. In particular, the large-scale distribution of granite and metamorphic rocks with abundant precipitation and differing topography constitutes the main area for the distribution of hot and warm springs, which are often distributed along faults or fault junctions, indicating the presence and development of anomalous geothermal heat (Fig.3). In basin areas, especially large basin areas, geothermal water with normal or abnormal formation pressures may be present. In general, the ground temperature gradient provides a good method to calculate the formation temperature at different depths. However, when abnormal formation pressures occur, hydrocarbon gases such as methane may be present. Hydrothermal geothermal energy has the most extensive distribution in China.

Table 1. Types of geothermal energy by heat carriers.

Type	Heat-carrying medium	Note
Hydrothermal	Water	High temperature (>150°C), medium temperature (90–150°C), low temperature (90-25°C); Further ,

Type	Heat-carrying medium		Note
			hot water (90-60°C), warm water (60-40°C), lukewarm water (40-25°C)
	Water and vapor		Hot water andsteam
	High temperature vapor		≥200°C dry steam
Rock-type geothermal	Hot dry rock	Non aqueous rock	Temperature 150–600°C
	Hot moist rock	Rocks with small amounts of water and vapor	
Magma geothermal	Magma	Incompletely cooled and consolidated magma bodies	Temperature 500–1200°C. Magma sacs or active volcanic passages
Hybrid geothermal	Surface water, groundwater, soil, rock etc.		Season Temperature difference, depth is less than 200m and temperature is 5–25°C

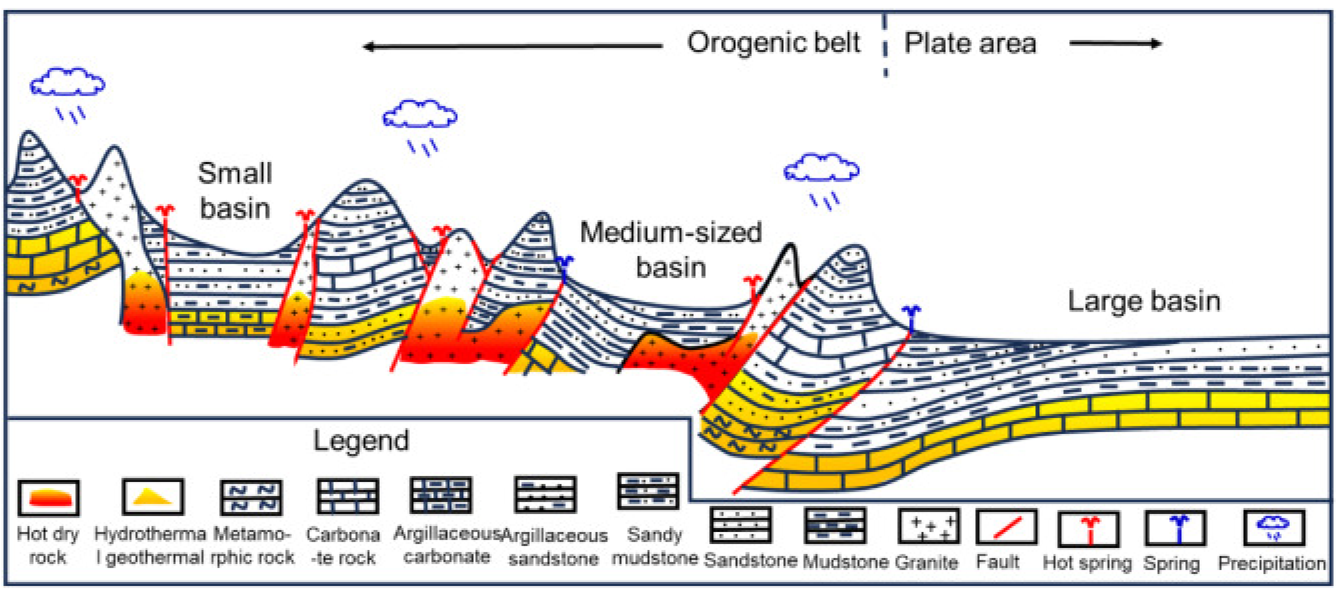

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Fig.3. Schematic diagram of geothermal type distribution in orogenic belts (uplift fold areas) and plate areas.

Hot dry rock is primarily composed of tight lithologies with high density, strong thermal conductivity, and the capability to conduct deep geothermal sources to shallow areas; granite masses with a heat generation ability are the best hot dry rock carriers. Hot dry rock masses that were buried early, especially granite bodies that are relatively young and well preserved, can often form hot dry rock geothermal sources with higher temperatures. The granite in the Gonghe basin of Qinghai Province has a high temperature because it has a sedimentary cover.

The shallow burial of magma sacs or magma that has not yet cooled, is cooling, or has just cooled in volcanic eruption channels provides more intense geothermal sources. However, because of the deep burial of magma sacs and the small sizes of volcanic passages, the effect of this type of geothermal energy in the usual sense is relatively limited. The Tengchong area in western Yunnan Province has developed hot springs and has good geothermal conditions, which are believed to be caused by volcanic activity.

Hybrid geothermal resources refers to geothermal resources with a burial depth of less than 200 m and a season temperature of 5–25 °C; the heat carrier can be surface water, groundwater, shallow formation water, soil, weathered crust, and/or bedrock. This type of geothermal resource, also known as a ground source heat pump, is widely used in northern China and is primarily related to off-season temperature differences caused by seasonal variations.

According to the type of geothermal carrier and the changing law of geothermal conditions in China, geothermal resources can be divided into several types, as listed in Table 2.

Table 2. Geothermal resource types in China.

Geothermal type		**Hydrothermal**	**Hot dry rock**
Basin area	Geologic background	The temperature of strata and formation water varies relatively steadily with depth, forming a strong geothermal gradient with strong variation patterns, and the development of hot springs is relatively rare	Most of them are acidic intrusive rocks or crystalline basement at the bottom of basins, with significant changes in lithology, large burial depth, and good heat caprock and heat preservation conditions
	Main types	Medium and deep hydrothermal type such as pore, cave, fissure, etc.Xiong'an region is a typical representative	Tight sedimentary rocks, crystalline basement, intrusive rocks,

Geothermal type		Hydrothermal	Hot dry rock
			etc.Granites in the Gonghe and Guide basins are typical representatives
Folded or uplifted area	Geologic background	Newer granite and gneiss regions can form shallow and abnormally high temperature hydrothermal geothermal energy, forming hot springs or crack type abnormally high temperature geothermal energy	Newer geothermal source rocks such as granite and gneiss, as well as intrusive rocks, tight sedimentary rocks, and tight metamorphic rocks in direct contact with them, are all high-quality hot dry rocks
	Main types	Shallow anomalously high temperature type, medium-depth fracture type, medium-depth karst type. For example, Yangbajing and Yangyi in Xizang, Tengchong in western Yunnanprovince, and Ganzi in western Sichuanprovince	Exposed, shallowly or deeply buried granite type, metamorphic type. For example, Jiaodongand Liaodong peninsulas in Shandong and Liaoning province respectively, Rizhao area in Shandongprovince

Hydrothermal geothermal resources are widely distributed and can be found in both basin and folded uplift areas. Sedimentary rocks or Quaternary deposits have larger porosity and higher water storage capacities, and the temperature of the reservoir or formation water increases with depth. The temperature gradient in a basin is relatively stable, especially in large- and medium-sized basins.

From eastern China to western China, the basin formation temperature gradually decreases; this is closely related to the formation mechanism, ages, and regional dynamical geological backgrounds of the different basins. In basins in eastern China, the temperature gradient is generally greater than 35°C/km, e.g., in the Songliao and Bohai Bay basins, which are referred to as hot basins. Thecentral China basins have relatively low temperature gradients, generally between 30°C/km and 35°C/km; such basins include the Erlian, Ordos, and Sichuan basins, which are referred to as warm basins. In western China, the basin temperature gradient is generally less than 30°C/km, with such basins including the Tarim and Junggar basins, which are referred to as cold basins. As a result of their type and formation mechanism, magmatic activity and granite intrusion, sedimentation time, and caprock development, different areas of a basin can exhibit different temperature gradient changes. For example, the southern North China Basin was in a state of slow uplift and long-term depositional stagnation during the Mesozoic and Cenozoic and the Upper Paleozoic-dominated strata have an obviously low geothermal gradient. In western China, the Qaidam, Gonghe, and Guide basins are sandwiched by Yanshanian granite bodies or developed granite bodies at the bottom of the basins; this results inthe coexistence of hydrothermal and hot dry rock type geothermal resources with high geothermal temperature gradients.

In areas with relatively newly developed granite bodies, especially in basins or fold uplift areas with high radioactive element contents during the Yanshanian and Himalayan periods, the heat generated by granite has an additional impact on the geothermal gradient. This not only significantly increases the strata temperature gradient but also can form anomalously high geothermal heat or even produce many hot springs where conditions are suitable. In small- and medium-sized basins where granites, deep faults, and underground water systems are developed, anomalously high geothermal fluids can form at shallow depths, forming shallow high anomalous hydrothermal geothermal sources. In folded uplift areas with granite development, abundant surface water systems, complex fault systems, large differences in topographic elevation, and varied surface morphology, it is easy to form hydrothermal geothermal sources with abnormally high temperatures. According to observations, larger and more shallowly buried Yanshanian and Himalayan granite bodies are usually effective providers of additional geothermal sources. Late Paleozoic granite bodies can also be effective additional geothermal source providers; for example, the Lincang Paleozoic granite, whichis the largest exposed granite in western Yunnan Province, contains a series of hot springs. The Lincang granite body formed since the Jinning movement, with small granite bodies still intruding as late as the Yanshanian movement, and a composite granite body dominated by the Hercynian movement formed during multiple periods of intrusive activity. Inside and around the Lincang granite body, hot springs are widely distributed, which provides a basis and an example for determining whether a Late Paleozoic granite body can be used as an additional effective geothermal source.

Hot dry rock type geothermal heat is dominated by granite and a few metamorphic rock bodies with relatively young ages; these may be magmatic, metamorphic, and/or sedimentary rocks with higher density, tight physical properties, and higher thermal conductivity coefficients that are in close contact with or directly adjacent to regional geothermal sources. In the basin area, intrusive granite, crystalline metamorphic basement rocks, and high-density sedimentary rocks can all act as effective hot dry rock destination layers. When a hot dry rock destination layer exists in the form of a protrusion, fault block, fault uplift, or uplift and has a small burial depth, it can combine the advantages of connecting to a deep geothermal source while being protected by a cap layer, forming hot dry rocks with higher temperatures. In 2017, high-temperature hot dry rocks with a temperature of 236°C were obtained from Triassic granites in the Gonghe Basin of Qinghai Province at the bottom of a 3705-m well.

The Yanshanian and Himalayan granites have dramatically altered the strata temperature variations, resulting in a significant increase in the geothermal temperature gradient. In the folded uplift area, exposed or shallowly buried granites are common hot dry rock destination layers. In localized areas in southwestern and northeastern China, magma sacs or recent volcanic activity currently exist and may have a beneficial effect on hot dry rock formation by directly providing residual thermal energy. However, the distribution of magma sacs is relatively restricted, and possible geomagnetic information anomalies have only been found in Tengchong [20] and Ning'er in western Yunnan Province [21]. Magma sacsare buried at large depths, with a low degree of implementation and unknown spatial distribution data, and are not suitable to be used as important sources of hot dry rock heat under present-day conditions. In areas with volcanic activity, the same problems, large burial depths of hot magma and small areas of influence of volcanic channels, make it difficult for these sources to substantially contribute to regional geothermal resources and therefore are not discussed here in a categorized manner.

4. Geothermal resource regions in China

China is tectonically composed primarily of the North China, Yangtze, and Tarim plates and a series of collisional orogenic belts. The three major plates are divided by the latitudinally oriented Yutian-Jiayuguan fault and Chifeng-Kaiyuan fault, the Yutian-Duran fault, and the Xiangfan-Guangji fault, respectively (Fig.4). Combined with the changes in the geotectonic and climatic conditions, China's geothermal resources can be divided into six regions:Southwest China, South China, Southeast China, North China, Northeast China, and Northwest China (Table 3).

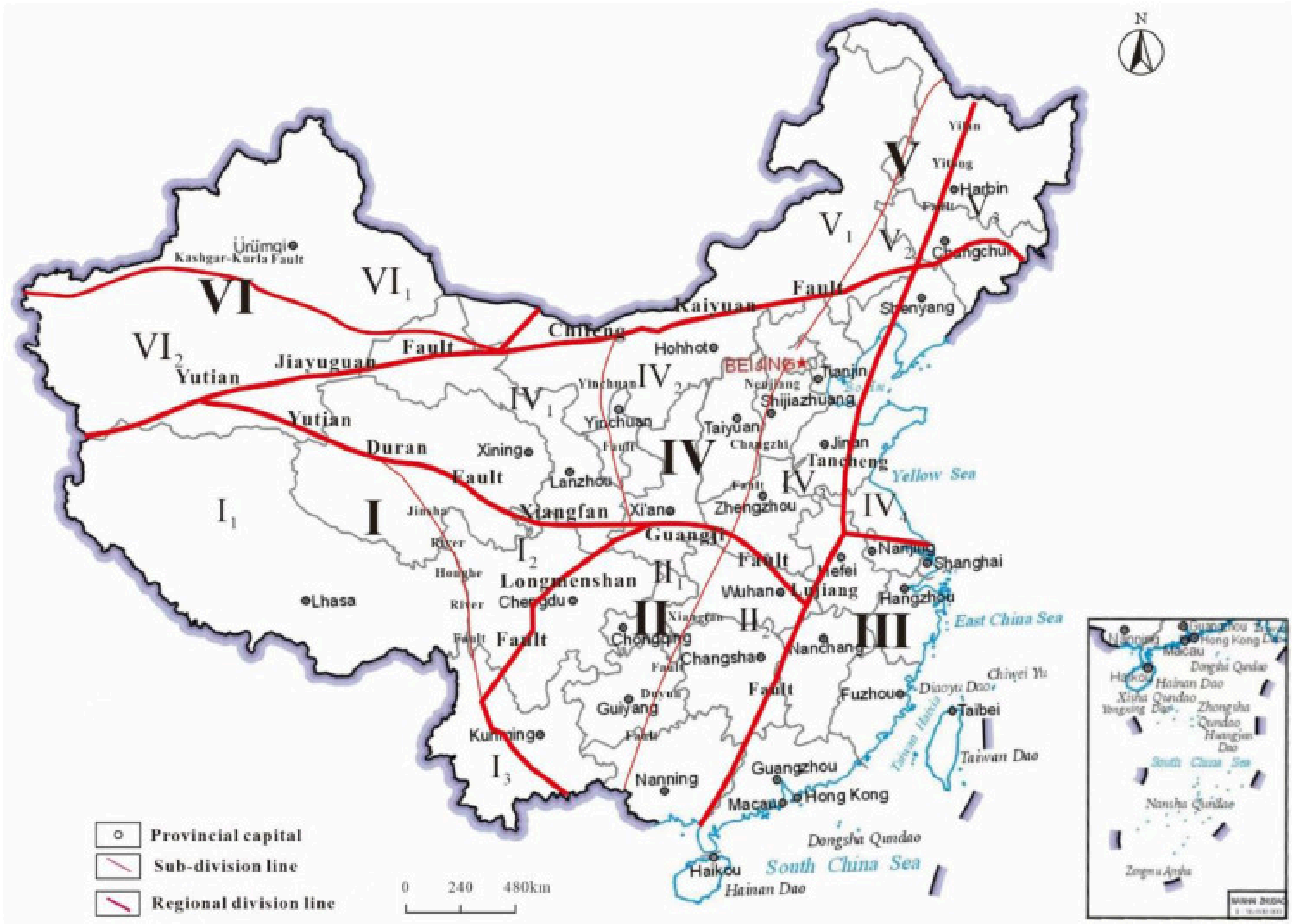

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Fig.4. Geothermal division map of China. (I) Southwest China region: (I_1) Xizang, (I_2) West Sichuan, (I_3) West Yunnan; (II) South China region: (II_1) Western South China, (II_2) Eastern South China; (III) Southeast China region; (IV) North China region: (IV_1) Qaidam-Qilian, (IV_2) Ordos, (IV_3) Bohai Bay, and (IV_4) Jiaoliao; (V) Northeast China region: (V_1) Daxing'anling, (V_2) Songliao, (V_3) Wandashan; (VI) Northwest China region: (VI_1) North Xinjiang, (VI_2) South Xinjiang.

Table 3. Geothermal resource divisions in China.

Region	Southwest China	South China	Southeast China	North China	Northeast China	Northwest China
Subregions	Xizang, West Sichuan, West Yunnan	Western South China, Eastern South China		Qaidam-Qilian, Ordos, Bohai Bay, Jiaoliao	Daxing'anling, Songliao, Wandashan	North Xinjiang, South Xinjiang

Region	Southwest China	South China	Southeast China	North China	Northeast China	Northwest China
Geologic Unit	Yunnan-Xizang orogenic belt	Yangtze plate	South China orogenic belt	North China plate	Xing'anling-Inner Mongolia orogenic belt	Tianshan-Inner Mongolia orogenic be and Tarim plate
Geothermal conditions	Affected by Indian Plate, the region is high altitude and high heat flow with abundant hot springs. Geothermal is strong westwards and southwards	It is dominated by huge marine sediments, and the magmatic activity is weak. Geothermal heat does not develop, but gradually increases to the east	Affected by Pacific Plate, the terrain changes significantly with high heat flow and abundant hot springs. Geothermal is strong southeastwards	Affected by Pacific and Indian plates, the terrain is flat with fewer hot springs. The heat flow increases eastward	Less affected by Pacific Plate, the terrain is flat with few hot springs. The heat flow decreases westwards	The heat flo is generally low and decrease westwards. Hot springs appear in t northwest
Geothermal Types	Medium-high temperature hydrothermal geothermal in deposit areas and hot dry rocks in granite and metamorphic rock areas	Basin areas are medium-low temperature hydrothermal. There can developed medium - high temperature hydrothermal and hot dry rocks eastwards	Medium-high temperature hydrothermal geothermal in deposit areas and hot dry rocks in granite and metamorphic rock areas	Hydrothermal constrained by geothermal gradients and hot dry rocks composed of sedimentary or metamorphic rocks within basin. hot dry rocks in granite areas	Hydrothermal constrained by geothermal gradients within basin and hot dry rocks in granite areas	Hydrother constrainec by low geothermal gradients within basi and hot dry rock

Southwest China includes the Xizang, western Sichuan, and western Yunnan provinces, with high altitudes, rapid topographic changes, and abundant surface water resources. The neotectonic movement in this region is intense, with intense tectonic movements, severe uplift and erosion, and orderly fractures. The Yanshan and Himalayan granites and metamorphic rocks are developed, and the granites gradually become younger southward. From northwest to southeast, the construct transformations from the northwest, east–west, northwest, to north–south directions are obvious and the tectonic basins are narrowand mainly small- and medium-sized. The region is rich in geothermal energy resources of various types; thisis not only the most favorable area for hot springs in China but is also the best area for the submission of medium and deep hydrothermal and hot dry rocks, among which the geothermal geologic conditions of the southern Xizang area are the best. The region can be further divided into the Xizang, western Sichuan, and western Yunnan subregions, where the heat flows and temperature gradients have obvious characteristics of being strong in the west and weak in the east and strong in the south and weak in the north. The geothermal geological conditions in this region are superior, with rich geothermal resources of various types, and China's famous high-temperature hot springs and large-scale geothermal power stations are all found in this area. The shallow and middle-depth hydrothermal type and the exposed, shallow buried and basin hot dry rock geothermal type are widely distributed in this large-area and high-temperature region, which is the best geothermal resource distribution area in China.

The South China region includes a vast area east of the Ailaoshan and Longmenshan mountains, south of the Qinling-Dabieshan mountains,and west of the southern section of the Tancheng-Lujiang fault. The main body consists of the Yangtze Plate with its complex terrain and abundant water resources. The region is primarily composed of thick and stable Paleozoic carbonate rocks and is characterized by a northeast-oriented tectonic pattern, lacking a regional distribution of granite bodies as geothermal sources. The neotectonic movement is relatively calm, resulting in a lack of active geothermal energy over a large area. Here, the geothermal gradient is relatively shallow,the hot spring temperatures are relatively low, and the geological conditions for geothermal development are average.

The Southeast China region has complex topography, abundant rainfall, and many Yanshan granite bodies, forming a large number of active hot springs with gradually increasing heat flow and geothermal gradients from northwest to southeast. The geothermal energy types are mainly mid-deep hydrothermal and hot dry rock types, and the neotectonic movement has led to the generation of active geothermal anomalies.

The North China region is situated on the North China Plate and is relatively stable; here,the influences of the Indian and Pacific plates are both drastically reduced. Warm and lukewarm springs in this region are primarily distributed along the Qinling, Taihangshan, and Yanshan mountains and along the east Shandong and east Liaoning uplifts. The region can be divided into four subregions with gradually increasing geothermal heat flows and geothermal temperature gradients at the east and west ends. The west subregion is primarily composed of the Qaidam Basin and Qilian fold, with Yanshanian granite, mainly developing hot dry rocks and high-temperature hydrothermal geothermal sources. The Ordos Basin subregion has stable sedimentation and a low geothermal gradient and lacks a distribution of springs. The Bohai Bay Basin subregion is composed of the Bohai Bay Basin andthe southern North China Basin, as well as other basins,and has a relatively high geothermal gradient. Located in the eastern part of the region, the Jiaoliao uplift is composed of the east Shandong and east Liaoning with Yanshanian granite and small and miniature basins with relatively high geothermal heat flows. This region is primarily composed of inter-distributed basins and folded belts in which the basins have high geothermal gradients, except for the Ordos Basin, forming good medium-depth hydrothermal sources. The region is favorable to shallow buried basins and deep buried hot dry rocks. The favorable geothermal types in this region are hydrothermal in the central basins and exposed or basin granite hot dry rocks on the east and west ends.

Yanshanian granite is widely distributed in the Northeast China region; however,the Cenozoic tectonic activity is light. Except for local volcanic activity, the impact of the neotectonic movement is relatively small and there are almost no exposed hot or warm springs. The Songliao Basin, located in the central subregion, has abnormally high geothermal heat flows and geothermal gradients. This area hosts primarily medium to deep hydrothermal type sources controlled by the basin and shallow to deep basin type hot dry rocks constrained by magmatic belts.

The main body of the Northwest China region consists of the Tarim Plate and the Tianshan-Nei Mongolia fold, which is stably subsiding and is an area of active sedimentation. It is primarily composed of basins and Late Paleozoic granites. Yanshanian granites are only developed in the Tashkurgan area on the west side of the Tarim Basin. The climate in this area is arid, and warm and lukewarm springs are primarily distributed in the western mountainous areas, with moderate to low temperatures. The basins in this area are all cold basins with low geothermal gradients, general geothermal conditions, and limited types of geothermal resources.

Geothermal source provide the primary focus of the main controlling factors for the formation and distribution of geothermal energy. Although many types of geothermal sources exist, granite, which is rich in uranium–thorium–potassium radioactive elements, is the most prevalent geothermal source in China. According to an analysis of granites from the Yanshanian and Himalayan periods, namely the main geothermal sources, the Southwest China region (I), Southeast China region (III) and the Qaidam-Qilian subregion (IV_1) in the North China region with Mesozoic and Cenozoic granites are the most favorable areas for high-temperature hydrothermal and hot dry rocks (Fig.5).

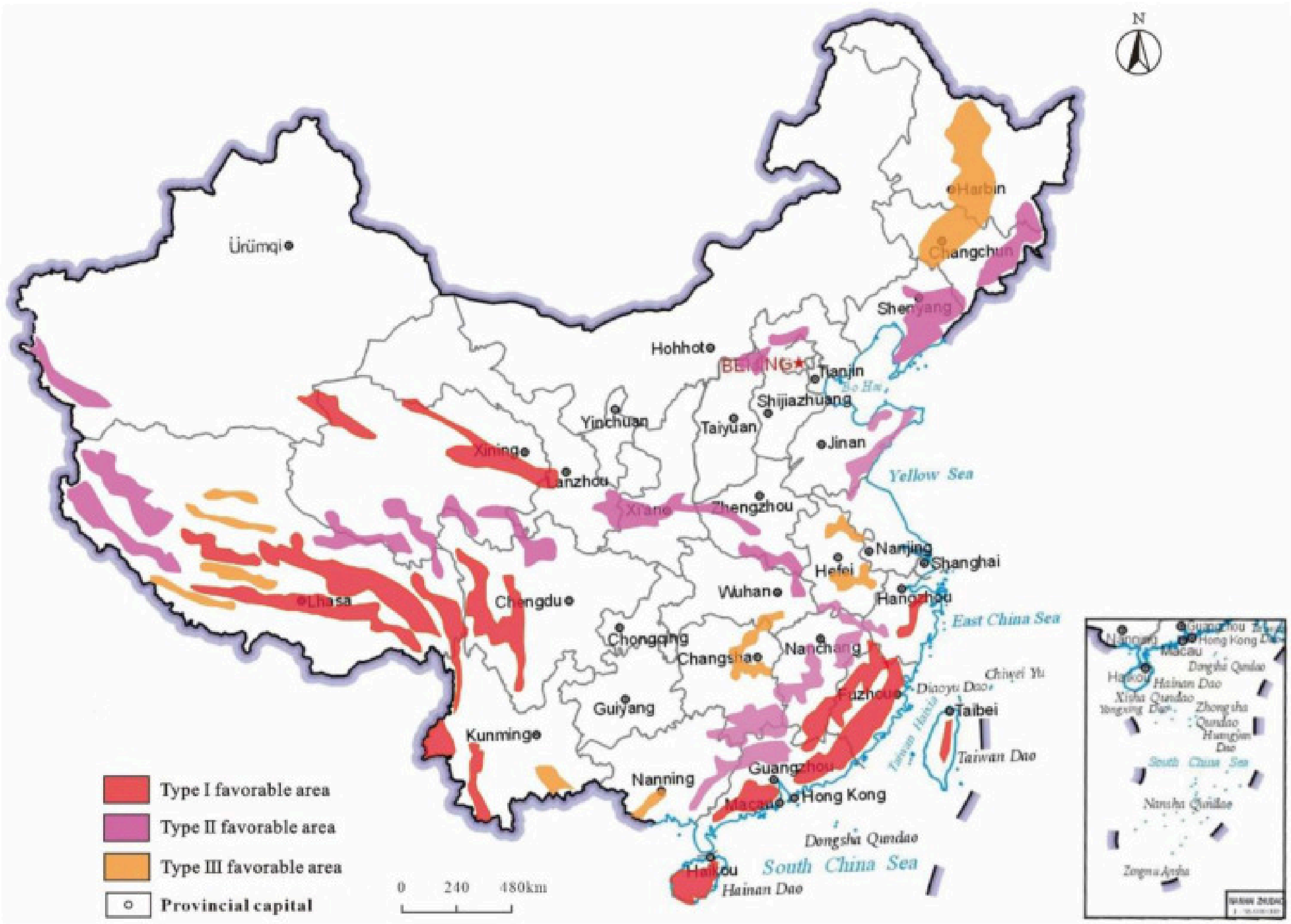

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Fig.5. Map of the favorable geothermal distribution areas in China based on the geothermal source distribution.

5. Prospects for the development and utilization of geothermal resources in China

Many researchers have estimated the potential of the geothermal resources in China, and all of them agree that China has great potential and prospects for the development and utilization of geothermal resources [[22], [23], [24], [25], [26]]. However, to date, the research and evaluation of geothermal resource exploration and development in China are still in their initial stages and primarily focus on shallow hydrothermal geothermal utilization.

As a result of regional tectonic constraints, China developed a series of Mesozoic and Cenozoic granite bodies in different provinces, including in southern Xizang, western Sichuan, western Yunnan, southern Hainan, southeastern Guangdong, eastern Fujian, northern Qinghai, southern Gansu, southern Shaanxi, western Henan, southern Anhui, western Jiangsu, eastern Shandong, northern Shanxi, northern Hebei, northern Beijing, Tianjin, eastern Nei Mongol, eastern Liaoning, eastern Jilin, etc. These granite bodies are effective geothermal sources for the development of high-temperature abnormal geothermal energy, which provide a basic guarantee for hydrothermal and hot dry rock resources in corresponding regions. China has discovered hot dry rocks in areas such as the Gonghe Basin in Qinghai and Weihai and Rizhao in Shandong Province, with the highest geothermal gradient discovered in the Gonghe Basin reaching 58.3 °C/km.

Basins are important locations for the convergence of underground high-temperature hot water. Although there are various geothermal gradients in these basins, the temperature of the formation water in a reservoir can meet industrial requirements when the depth reaches a certain critical level. Average geothermal gradients in the warm basins in eastern China are as high as 35 °C/km, and the calculated temperature of the formation water can exceed the 120 °C required for economic power generation when the drilling depth reaches 3000 m. If the ground temperature gradient is 40 °C/km, the reservoir temperature can reach 150 °C at a depth of 3300 m. In the cool basins in western China, the ground temperature gradient and heat flow are lower. According to the average ground temperature gradient of 27 °C/km, the reservoir temperature at a depth of 4000 m can be more than 120 °C. Moreover, there are many drilling wells for oil and gas in these basins and these wells can be changed into geothermal development wells via technological modifications after oil extraction is completed. Of course, sandstone formations with high porosity and permeability and carbonate rocks with developed pores, karst caves, and fractures are favorable characteristics for both geothermal water target strata and oil and gas reservoirs. The limestone of the Ordovician Majiagou Formation has a large development area in North China and a large variation in its burial depth; however, the pores, karst caves and fissures are developed and the water content is large, making it an important geothermal water target layer.

Geothermal power generation in China is developing rapidly [[27], [28], [29]] (Fig.6 and Table 4). Since the power generation experiment in Fengshun, Guangdong, in 1970, China has completed power generation experiments on different types of geothermal resources. A complete technical foundation has been formed, and a complete technical system, from geological theory, exploration and evaluation, and development engineering to industrial power generation, is being constructed and improved.

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Fig.6. Distribution map of geothermal power stations and experimental power stations in China.

Table 4. Informationconcerning geothermal power stations and experimental power stations in China.

Geothermal power station/experimental power stations	Location	time	Geothermal water temperature/°C	Generation method	Installed capacities	Supplements
Gonghe	Qinghai	2022	153	ORC	340 kW	Hot dry rock
Matouying	Tangshan, Hebei	2021	150	ORC	280 kW	Hot dry rock
Tianzhen	Datong, Shaanxi	2021	160	ORC	580 kW	Hot dry rock
Xianxian	Hebei	2017	95–104	ORC	280 kW	Hydrothermal
Ruili	Dehong, Yunnan	2017	103	ORC	1.2 MW	Hydrothermal
Kangding	Sichuan	2017	218	ORC	280 kW	Hydrothermal
Tianjin	Tianjin	2015	85	ORC	90 kW	Hydrothermal
Gonghe	Qinghai	2014	84	ORC	114 kW	Hydrothermal
Renqiu	Renqiu, Hebei	2013	105	ORC	500 kW	Hydrothermal
Yangyi	Dangxiong, Xizang	2011	150–209	ORC	16 MW	Hydrothermal
Tengchong	Yunnan	2005	250	ORC	12 MW	Hydrothermal
Nagchu	Xizang	1993	114	ORC	1 MW	Hydrothermal
Langjiu	Ali, Xizang	1987	105	Flash	2 MW	Hydrothermal
Tuchang	Taiwan	1983	173	Flash	300 kW	Hydrothermal
Yilan	Taiwan	1981	93	Flash	3 MW	Hydrothermal
Reshuicun	Xiangzhou, Guangxi	1979	73–79	Flash	200 kW	Hydrothermal
Tangdongquan	Zhaoyuan, Shandong	1979	91–98	Flash	300 kW	Hydrothermal
Yangbajing	Dangxiong, Xizang	1977	140–160	Flash	26 MW	China's first high-

Geothermal power station/experimental power stations	Location	time	Geothermal water temperature/°C	Generation method	Installed capacities	Supplements
						temperature geothermal power station
Qingshui	Taiwan	1977	99	Flash	3 MW	
Huitang	Ningxiang, Hunan	1975	92–98	Flash	300 kW	Hydrothermal
Xiongyue	Gaixian, Liaoning	1973	75–84	ORC	200 kW	Hydrothermal
Wentang	Yichun, Jiangxi	1971	66	ORC	50 kW	The lowest temperature geothermal station in the world
Houhaoyao	Huailai, Hebei	1971	79–85	ORC	200 kW	Hydrothermal
Deng wu	Fengshun, Guangdong	1970	92	Flash	300 kW	China's first geothermal test power station

ORC: Organic Rankine cycle; Flash: Flash vaporization system.

China has developed or is currently developing new geothermal utilization methods; these include direct applications in industries, people's livelihoods, agriculture, forestry, animal husbandry, fisheries, medical industry, geological and mineral development, and environmental protection. The utilization of geothermal resources also includes indirect applications in fields such as power generation, energy storage, and industrial steam, as well as multi-energy complementary and comprehensive applications in new green energy fields such as solar energy, wind energy, and biomass energy and cascade utilization in various comprehensive utilization techniques.

Geothermal fluids in long-term contact with different lithological strata or rock masses are good corrosion or precipitation agents, and their fluidity can enrich mineral elements (such as lithium metal), especially rare elements, to form objects for industrial development, forming high abnormal concentrations of hydrogen, helium, and other rare gases, bringing added value to geothermal development.

China's geothermal energy industry is entering the fast lane of industrial technological development and will achieve further significant development soon. Under the background of carbon peaking and carbon neutrality goals and vigorously developing green energy, China's geothermal development and utilization are in a critical period of transition from the direct utilization of shallow water heat types to the direction of high-temperature geothermal or hot dry rock power generation in middle and deep layers.

(1) It is necessary to strengthen research and form a geothermal theoretical system suitable for China's geological conditions, systematically establishing geothermal development models of different types, regions, and geological conditions. One important task is to capture the main geological factors controlling the geothermal distribution and to predict the geothermal distribution law of the geothermal energy.

(2) It is important to develop economical, fast, effective, and applicable geothermal exploration, development, and utilization technologies. The main goal is to surpass large-scale application technologies such as forecasting, drilling, exploitation, and utilization, develop low-cost geothermal development and comprehensive utilization technologies, and form an economical and efficient series of core methods and key technologies.

(3) It is time to develop a policy that encourages the development of the geothermal industry. The main goal is to open a green channel; create a more suitable environment; further encourage geothermal exploration, development, and comprehensive utilization; and promote the rapid development of the geothermal industry.

6. Conclusions and suggestions

(1) Geothermal formation requires mechanical elements such as geothermal sources, geothermal reservoirs, heat transmission, heat caprock, and heat preservation, of which the geothermal source is the most important factor.

According to the type of heat carrier, geothermal resources can be divided into four types:hydrothermal, rock-type geothermal, magma geothermal, and hybridgeothermal. China's geothermal energy can be divided into hydrothermal and hot dry rock types in basins and orogenic belts. Geothermal energy in basin areas is dominated by the hydrothermal type, and geothermal energy in orogenic belts with granite include both hydrothermal and hot dry rock types.

(2) China has complex geological conditions, diverse types of geothermal resources, and broad prospects for development and utilization. As a geothermal source, the Yanshanian and Himalayan granite bodies are widely distributed with the widespread development of deep and large faults. The influence of neotectonic movements is widespread, giving rise to diverse geological conditions for geothermal development.

(3) China can be divided into 6 distinct geothermal regions and a further 13 geothermal subregions, of which the Southwest and Southeast China regions and the Qaidam-QIlian and Jiaoliao subregions in the North China region with Mesozoic and Cenozoic granites are the most favorable areas for high temperature hydrothermal and hot dry rock sources.

(4) The prospects for geothermal development and utilization in China are broad. China's geothermal development and utilization are in a critical stage of transition from the direct utilization of shallow water heat types to high-temperature geothermal or hot dry rock power generation in middle and deep layers. Basic theoretical research, key technological breakthroughs, and policy incentives are the main issues that need to be addressedin the geothermal industry.

Funding

This paper was supported by the National Natural ScienceFoundation of China (41927801), the Major Special Project ofYunnan Province (202302AF080001), and the Key Research and Development Program of Yunnan Province (202303AA080006).

Conflict of interest

Jinchuan Zhang is an editorial board member/editor-in-chief for Natural Gas Industry B and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

Acknowledgements

The authors gratefully acknowledge the financially supportof the National Natural Science Foundation of China (41927801), the Major Special Project of Yunnan Province (202302AF080001), and the Key Research and Development Program of Yunnan Province (202303AA080006).

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Peer review under responsibility of Sichuan Petroleum Administration.