

Towards a New Classification Scheme of Geothermal Systems in China

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Keywords: geothermal system, classification, China

ABSTRACT

Classification of geothermal systems provides good basis for exploration and assessment of geothermal resources. China is rich in geothermal resources and genetic mechanisms are diverse with complicated geological backgrounds. In this paper we propose a new classification which is based on the type of heat source, followed by mechanism of heat transfer. Four types of tectono-genic heat sources are identified and two types of heat transfer mechanisms have been used for the classification. The dominant factor in determining the uneven distribution or accumulation of heat energy in the crust is emphasized. Other influencing factors are used to further classify the resources into subcategories. Geothermal prospects or plays in the Himalayas are considered to be supplied with crustal magmatism/partial melting, caused by collision-induced conversion from mechanical to heat energy. Geothermal resources in some of the hot and warm basins in eastern and central China are fed by elevated heat flux from mantle upwelling in a rifting tectonic background. Typical examples are the Bohaibay, Songliao and Guanzhong Basins. Mantle heat also dominates those geothermal systems found in regions with recent volcanic activities. Good examples are Tengchong geothermal field in SW China and probably Changbaishan geothermal play in NE China. Deep faulting also induces heat accumulation in the crust that serves as an additional heat source, which is found in major fault zones. Tanlu fault zone in eastern China is a typical example of this kind, so are those in SE China, including Zhangzhou, Fuzhou geothermal fields. Geothermal systems with dominant radiogenic heat generation from radio nuclides have not been confirmed but maybe a new type to be discovered in China. This classification scheme is expected to be more effective in guiding exploration and assessment of geothermal resources. The search for deep geothermal resources (hot dry rock) should also benefit from this fundamental understanding and theoretical classification.

1. INTRODUCTION

Classification of geothermal systems provides necessary basis for exploration and assessment of geothermal resources. Different geothermal systems may require designing exploration schemes and adopting assessment methods which best fit the objective geothermal systems. China is rich in geothermal resources distributed all over the country. There have been different classification schemes developed and used in the country in the past.

Geothermal systems in China are currently classified by reservoir temperature. According to the latest national standard for geologic exploration of geothermal resources (national standard of People's Republic of China), the geothermal resources are divided into three types: 1) high temperature geothermal resources ($T \geq 150^\circ\text{C}$), 2) inter-medium temperature ($150^\circ\text{C} > T \geq 90$), 3) low temperature geothermal resources ($T < 90^\circ\text{C}$). The geothermal resources in different temperature scales play diverse roles in national economy and people's life. The high temperature resources are mainly used for power generation. The inter-medium temperature resources are mainly used for drying, cooling and space heating. The low temperature resources are mainly used for physiotherapy, bathing, greenhouse and cultivation. This classification standard has been widely used in China and recognized as a useful standard in geothermal development and utilization.

The conventional classification scheme based on geothermal reservoir temperatures is very useful in making plans of utilization. However, with the evolving trends in utilizing more and more geothermal heat in other forms, for example hot dry rock resources, the limitation of this kind of classification scheme is encountered with problems. Based on the reservoir temperature, the existing classification scheme provides little geologic information especially the tectonic background which is closely related to the heat source of a geothermal system/prospect. Thus, the vital factor resulting in the forming of a geothermal system is hardly shown. The genesis of an existing geothermal system, either high temperature or low temperature, has guiding significance in the design of exploration programs, selection of assessment method and further prediction of new geothermal prospects.

In short, the search for geothermal resources is governed by the general laws of heat accumulation in the earth's crust at economic depths. This has not been included in the existing classification scheme. There is a need for a new scheme of geothermal system classification.

2. CLASSIFICATION SCHEME

Since the heat source is the vital factor in forming of a geothermal system and the importance of genesis in either geothermal exploration or assessment, we propose a new classification which is based on the type of heat source, followed by mechanisms of heat transfer. Four types of tectono-genic heat sources are identified and two types of heat transfer mechanisms have been used for the classification.

According to its interior structure, the solid earth is made of crust, mantle and core. Fundamentally, the genesis of a geothermal system in depth is the result of uneven distribution or accumulation of heat energy in the crust, or more specifically, the upper crust. Since the heat energy in crust originates from the crust itself or the mantle underneath it, we can roughly divide the heat source of geothermal systems into two types, thus the crustal source and the mantle source. Crustal source can be divided into crustal magmatism/partial crustal melting and dominant radiogenic heat generation, and the mantle source can be divided into pure mantle upwelling and with recent volcanic activities.

Subcategories of geothermal systems are based on the heat transfer mechanism in the geothermal reservoirs. When taking the heat transfer mechanisms into consideration, four types of geothermal systems can be subcategorized into conduction subcategory and convection subcategory. Conduction is the transfer of heat from one part of body at a higher temperature to another part of the same body at a lower temperature (Rohsenow, 1998). Convection relates to the transfer of heat from a bounding surface to a fluid in motion, or to the heat transfer across a flow plane within the interior of the flowing fluid (Rohsenow, 1998). These subcategories then form different types of geothermal reservoirs.

3. GEOTHERMAL SYSTEMS IN CHINA

Based on the general tectonic framework and the current understanding, geothermal systems in China are classified into four types: 1) crustal magmatism/partial crustal melting, 2) dominant radiogenic heat contribution, 3) pure mantle upwelling, 4) with recent volcanic activities.

Based on the heat transfer mechanism, every type can be further subclassified into two subcategories: 1) conduction subcategory and 2) convection subcategory. We will discuss these categories in details below.

Chinese continental lithosphere comprises of three tectonic domains: (1) eastern China, a region characterized by rifting, extensional basins, and voluminous basaltic volcanism; (2) central China, a plexus of cratonic terrains with low-heat flow (40-50mW/m²), including the Tarim, Erdos, and Yangtze blocks welded by pre-Cenozoic orogenic belts; and (3) western China, a region comprising the Qinghai-Tibet-Himalayan orogen. The relatively thin crust (~35km) and lithosphere (~70km) of eastern China is believed to reflect mantle upwelling. Thickened crust (~70km) and lithosphere (>150km) in western China reflect the advanced development of an orogen root (Deng et al., 2004). In eastern China, the mantle upwelling provides the heat source for geothermal systems in sedimentary basins and volcanic regions. In western China, the collision-induced crustal shortening and deformation provides the heat source for geothermal systems in the Tibetan Plateau.

What calls for special attention is the crustal thinning in orogen belts. Although the geological relationship suggests compressional forces caused both by mountain building and by orogen root development, extensional stress resulting from gravitational collapse is believed to have induced lithospheric and crustal thinning (Deng et al., 2004). A good example is Tengchong geothermal system in southwestern China.

3.1 Crustal heat source

3.1.1 Crustal magmatism/partial melting

The forming of granite magma starts from the partial melting of middle-lower crust. Magma chambers in depth result from the crustal magmatism or partial melting. The crustal magmatism is in need of enough heat energy. The heat energy which drives the crustal magmatism can come directly from mantle or indirectly from the transfer of other energy. In the Himalayan geothermal belt in China, the collision of Indian-Eurasian plates leads to the intensive uplift of Tibetan Plateau and crust shorting/thickening. Various faults emerge in response to the collision event in Cenozoic. Blocks limited by faults escape away from the main collision region. In the process of collision and escaping, the mechanical energy, such as the friction heat and the plastic deformation heat, can be converted into heat energy. This collision-induced heat may cause the crustal magmatism/partial melting, thus the forming of magma chambers in depth. The magma chambers in the crust are very good heat source of high temperature geothermal systems.

A good example is Kangding geothermal field in southwestern China (Fig. 1). Kangding geothermal field is located in the eastern margin of Tibetan Plateau and near the eastern Himalayan syntaxis. The eastern Himalayan syntaxis, which results from the geometrical shape of Indian plate and Indian-Eurasian plate collision, is the region with the most intensive plastic deformation. Therefore, the amount of heat energy transferred from the mechanical energy is significant, which makes it possible to meet the requirement of crustal magmatism/partial melting. Besides, the geophysical evidence manifests that there indeed exists a high conductive body in eastern margin of Tibetan Plateau. In this collision tectonic background, the region near the Himalayan syntaxis in China has an exciting prospect of high temperature geothermal resources. This type of geothermal systems in China has the heat source coming from crustal magmatism/partial melting.

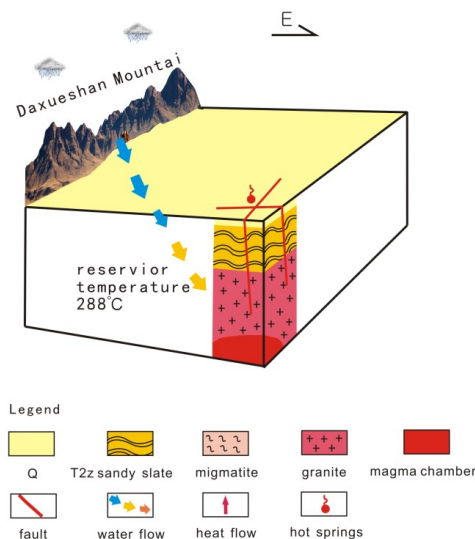


Figure 1: Conceptual genetic model of Kangding geothermal field

3.1.2 Radiogenic heat generation

In addition to the crustal magmatism/partial melting, another type of crustal heat source is the heat generated from the decay of radioactive elements in crust. In crust, this part of heat mainly comes from decay of three kinds of radioactive elements, thus uranium, thorium and potassium. By measuring the contents of uranium, thorium and potassium in different rocks, we can calculate the heat generation rate of rocks respectively. Earth is a complicated system, and it has been continuously differentiating and evolving since it had been formed. In the process of differentiating and evolving, uranium, thorium and potassium commonly enrich in crust and top of upper mantle. Acidic magmatic rocks in the upper continental crust are most enriched with uranium, thorium and potassium. In regions where rocks are enriched with significant content of uranium, thorium and potassium, the dominant heat source of geothermal systems can be radiogenic heat. Geothermal systems with dominant radiogenic heat contribution from radio nuclides have not been confirmed but maybe a new type to be discovered in China.

3.1.3 Deep faulting also induces heat accumulation in the crust that serves as an additional heat source from the crust, which is found in major fault zones. Those geothermal systems in SE China, including Zhangzhou, Fuzhou geothermal fields.

3.2 Mantle heat source

3.2.1 Pure mantle upwelling

In the eastern and central China, the tectonic background is a rifting environment. Previous studies indicate that the Cenozoic continental lithosphere mantle of North China has obvious activity and juvenility (Deng et al., 1990; Deng et al., 1992; Zhou et al., 1985; Zhou et al., 1988). The Cenozoic continental lithosphere mantle presents a sharp contrast to the old Craton, but is in accordance with Cenozoic rift basin, intensive volcanic activity and observations of earthquakes and geothermal anomaly (Zhou, 2006). The widespread and intensive activity of deep matter is a key factor inducing the lithospheric thinning of North China, increase of geothermal gradient, forming of North China rifts and development of sedimentary basins (Zhou et al., 1985). The diapirism of upper mantle asthenosphere results in the change of lithosphere thickness of North China in Cenozoic from 157km to 60km. It's the outcome of an active rift. Also Due to the diapirism of upper mantle asthenosphere or mantle upwelling, the geothermal gradient elevated and geothermal resources in eastern/central China are fed by elevated heat flux. Typical examples are the Bohaibay and Songliao Basins.

Taking the Bohaibay Basin as an example, it is a Mesozoic and Cenozoic basin located on the eastern block of the North China Craton. It is the central region of the destruction of the North China Craton (Li et al., 2010). During the destruction of the North China Craton, the tectonism of Bohaibay basin is the Mesozoic extrusion tectonics, local delamination and magma underplating and the Cenozoic NW-directed crustal extension (Li et al., 2010). The extension and delamination lead to the elevation of geothermal gradient and heat flux. The geothermal resources in Bohaibay Basin is the result of mantle upwelling which acts as the heat source of geothermal systems. Niutuozen geothermal field (Figure.2) is typical in northern China and its genesis is closely related to the destruction of the North China Craton.

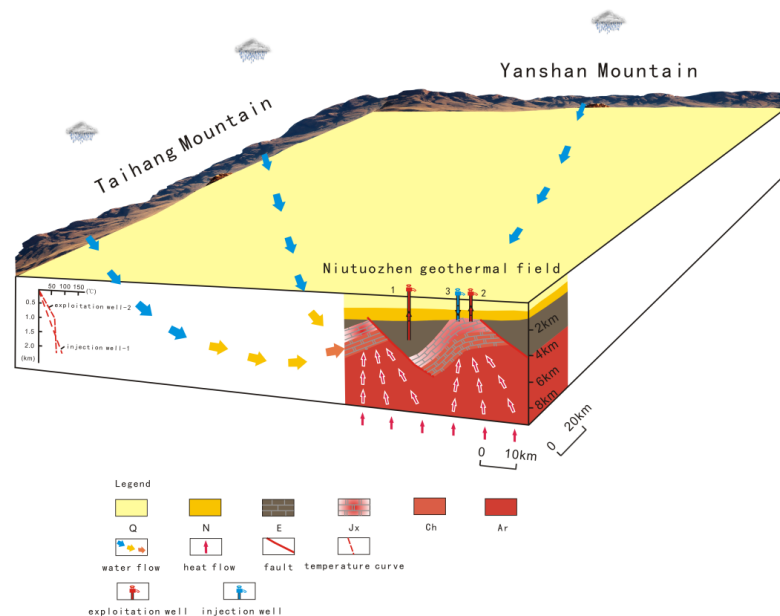


Figure 2: Conceptual genetic model of Niutuozen geothermal field

3.2.2 Recent volcanic activities

In addition to the sedimentary basins in rifting background, mantle heat is also dominating those geothermal resources found in regions with recent volcanic activities. In the East Asia continent there are many Cenozoic volcanoes, but only a few are still active now, such as the Changbai and Wudalianchi volcanoes in NE China and Tengchong volcano in SE China (Liu, 1999; Liu, 2000). The three active volcanoes have erupted many times in the history (Zhao et al., 2009).

Taking the Tengchong geothermal field in SW China for example, Tengchong region is an extinguished volcanic geothermal system in Himalayan geothermal belt (Mu et al., 1987). It's close to an active plate boundary and belongs to "plate boundary"

volcano (Wang et al., 2002). The eruption time of volcanoes is from the Miocene to Pleistocene with the climax occurring in the late Pleistocene. The volcanic rocks are mainly andesitic basalt and andesite (Mu et al., 1987). Previous geochemical studies imply that the magma of Tengchong Volcanoes originate from mantle as a basalt diaper, but the magma may have been contaminated by crustal material (Mu et al., 1987). The geophysical studies also indicate that there is a low velocity abnormal body in upper crust in the Tengchong area. Both the crust and the upper mantle of Tengchong volcano-geothermal area are characterized by low P-wave (Wang et al., 2002). The magma in the crust in Tengchong is derived from the upper mantle (Wang et al., 2002). The upwelling hot matter originated from the upper mantle move to upper crust and even earth surface, forming the magma chamber in upper crust and volcanic cluster in the earth surface. Therefore, Tengchong volcanic geothermal system is typical geothermal system from heat source of recent volcanic activities. Just like the mantle upwelling, mantle heat is the key factor in the genesis of this type of geothermal system.

Another example is the Changbaishan geothermal play in NE China. In NE China, Cenozoic intraplate volcanic products are widely distributed, clearly associated with major regional fault systems (Takeshi Kuritani et al., 2009). Changbai intraplate volcano is located close to the boundary between China and Korea (Zhao et al., 2009). Such volcanic activity appears to have first appeared in the late Cretaceous, and, with minor interruptions, continues to the present time (Liu et al., 2001). Zhao et al. (2009) determines P-wave tomography of the crust and upper mantle under the Changbai volcanic area. His result suggests that the formation of the Changbai and other intraplate volcanoes in NE Asia is related to the upwelling of hot and wet asthenospheric materials in the big mantle wedge above the stagnant Pacific slab. Geochemical studies of Chen et al. (Chen et al., 2007) and Zou et al. (Zou et al., 2008) suggest that the primary cause of the magmatic activity in NE China is considered to have been decompression melting of the asthenospheric mantle associated with lithospheric thinning, subduction of the Pacific plate, or upward thickening of the stagnant Pacific slab. Thus, the active intraplate volcanoes in NE Asia are not hotspots related to deep mantle plumes but are caused by plate tectonic processes in the upper mantle and the mantle transition zone (Zhao et al., 2009). The upwelling of mantle which is caused by plate tectonic process leads to the magmatic and volcanic activities in NE China. The heat source of Geothermal systems in Changbaishan comes from recent volcanic activities caused by mantle upwelling.

3.2.3 Deep faulting also induces heat accumulation in the crust that serves as an additional heat source from the mantle, which is found in major fault zones. Tanlu fault zone in eastern China is a typical example of this kind.

4. CONCLUSIONS

According to the type of heat source, we propose a new scheme of classification of geothermal systems in China. This classification scheme takes full consideration of tectonic background in China. There are four categories, which are crustal magmatism/partial crustal melting, radiogenic heat generation, pure mantle upwelling and recent volcanic activities respectively, corresponding to crustal shortening and thickening in western China and crustal thinning and mantle upwelling in eastern China.

Because the heat source is closely related to the tectonic background, this new classification will provide more geologic information for the further exploitation, assessment and prediction of undiscovered geothermal resources.

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