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A BRIEF REVIEW OF GEOLOGICAL STUDIES ON GEOTHERMAL SYSTEMS IN CHINA 1988-2008

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ABSTRACT

China has been listed on top of the list of countries in Direct Heating Use of Geothermal Resources in the world for the past decade and has not been surpassed so far. Hydrothermal resources have contributed with more than half of the total direct use even in recent years where ground source heat pumps have been widely used. Geological studies have provided support to various geothermal projects both in the exploration and exploitation stages. In this paper we provide a brief review of the history of development in the last two decades. Principles are introduced and case studies are used to discuss the following aspects of geological studies: geo-structural analysis, geophysical prospecting, isotopic analysis and thermodynamic modelling. The emphasis is on the application of the principles and methodologies for the exploration and management of low enthalpy geothermal resources in continental China.

1. INTRODUCTION

Although both high and low enthalpy geothermal resources are found in China, the focus of development has mainly been on low enthalpy systems in the last 20 years because of their convenient geographical location and the local energy demand. While geothermal electric power generation remains basically stagnant in China, geothermal development of low enthalpy systems for direct heating purposes has been booming, and China became the world's top user of geothermal heating more than a decade ago and that position has been kept since. Thanks to the market demand and the importance of greenhouse gas emission reduction, this trend will likely remain in the next decade.

Strongly driven by the energy and tourism markets as well as the real estate market, geothermal development projects have seen rapid increase in the last decade, especially in the large cities that are struggling to provide energy and heating supply for improved living and recreation under the stress of cutting back on energy consumption and greenhouse gas emissions.

One phenomenon is a clear indication of this "geothermal rush": in places where the geothermal gradient is lower than that of the global average (30°C/km), deep groundwater with temperatures slightly above 50°C is being exploited for direct uses. The water is extracted from great depths, usually > 2000 m but sometimes up to 4000 m. As these projects involve major initial investment in drilling and complications due to geological conditions, the risk is high compared to that of the development of conventional hydrothermal resources from shallower depths, where the geology is better understood.

This paper takes is reviewing the footprints we have left in the effort to develop and apply geological principles and to shed light on the formulation of new strategies to provide technical support to the market-driven and policy-guided boom of geothermal development in China.

2. STRUCTURAL ANALYSIS WITH EMPHASIS ON THE LATEST MOVEMENT

In a low enthalpy geothermal field the thermal anomaly is not as intense as in high enthalpy geothermal fields. It is often difficult to identify a thermal anomaly directly from soil temperature measurements. The formation mechanism of low temperature systems is dominated by geological structures, either the basement boundary topography in the case of conductive systems in sedimentary basins, or highly permeable fracture zones in the case of convective systems in crystalline terrains. Following the great achievements made by Chinese hydrogeologists led by Prof. Xiao Nansen (Xiao, 1986) in locating groundwater reserves in crystalline rocks, according to the principle of neo-tectonic structural analysis, we attempted to develop a similar principle to guide geothermal well siting in mountainous areas with the help of effective geophysical (resistivity) and nuclear physical prospecting methods that are sensitive to recent structural activities, such as fission track, as well as dating of precipitates in faults (thermo-luminescence) coupled with geomorphological analysis (Pang et al., 1989, Pang et al., 1993). These techniques have been successful in south-eastern China, i.e. Fujian, Guangdong, Hainan and Jiangxi Provinces, where vast granite intrusive bodies are present. In the case of sedimentary basins, we have applied the principle of fault-block tectonics developed by late Prof. Zhang Wenyou (Zhang, 1984), academician and former director of IGCAS. Satisfactory results have been achieved in the North China Basin (Chen, 1986), i.e. Beijing, Tianjin and Hebei provinces. Recently, with increased collaborations between hydrogeologists and geophysicists, this approach is getting strong technological support.

3. CHEMICAL THERMODYNAMICS FOR LOW TEMPERATURE RESERVOIRS

Equilibrium criteria for the application of chemical thermodynamics is a major issue in the study on water-rock interaction processes for the quality assessment of the water, and more importantly, for chemical geothermometry (Pang and Armannsson, 1989). Different approaches of thermodynamic modelling were made with different types of water analyses and the main influencing factors were identified, such as degassing, mixing of fluids, as well as erroneous chemical analysis of key elements like Aluminium and new procedures to solve the problems were formed. When the influencing factors and errors are corrected, most of the geothermal systems with temperature as low as 80°C, appear to reach equilibrium with certain mineral assemblages (Pang and Reed, 1998). This conclusion opens the door for thermodynamic applications to low enthalpy systems.

Zhangzhou geothermal system is formed by deep circulation of ground water in a Quaternary fault basin with a Mesozoic granite basement, the basin is approximately 500 km^2 in area (Pang, 1987; Wang et al., 1993). Fault systems make up the main geological structure of the basin and they serve as the conduit for geothermal water. The Quaternary aquifer and the granite fractured aquifer are the two main reservoirs. The thermal water from the system is saline; the total dissolved solids are 12 g/l in the water with highest temperature. The salinity is believed to originate from sea water, with a thermal water mixture of 30% sea water and 60% meteoric water, as estimated by Pang et al. (1995b).

Zhangzhou geothermal system has the highest observed temperature (114°C at the well-head and 122°C at a depth of 90 m) along the eastern coastal area of continental China. The reservoir temperature is a key to understanding the development mechanism and assessing the energy potential, including establishing an optimum development scheme of the numerous hot springs of similar type in the south-east China geothermal zone. Pang et al. (1990) and Pang et al. (1995a) estimated a reservoir temperature of 140°C by from a SiO_2 mixing model based on chalcedony equilibrium.

In order to obtain a more precise estimation of the reservoir temperature, it is necessary to study the water-rock interaction and equilibriua in the system in detail. New methods should be used in this respect, such as the Giggenbach Na-K-Mg geothermometer and "whole system chemical equilibrium calculation", and influencing factors should be evaluated (Pang, 1991).

From reconstructed equilibia a more precise reservoir temperature of 150°C was obtained, this is in good agreement with the values calculated from quartz geothermometry, modified Na-K-Mg relations and oxygen isotope geothermometry based on aqueous SO_4-H_2O. Exchange of ^{18}O between water and aqueous sulphate may have reached equilibrium in the system (Pang et al., 1996).

Chemical geothermometers and thermodynamic modelling approaches were used in temperature estimates for the Tertiary aquifers of the Xi'an area, which gave a reasonable temperature, around 130°C (Qin et al., 2005).

4. USING ISOTOPES TO UNDERSTAND GEOCHEMICAL PROCESSES

In low enthalpy geothermal systems, the origin of water and solutes are mostly from meteoric sources with limited input from deep volatiles. So the foci of studies are mostly on the interactions between different water reservoirs in the upper crust. However, it may become complicated when there are multiple sources of recharge in a dynamic regime. Isotope analyses are very useful in these cases.

Once again we use Zhangzhou geothermal field (ZGF) as an example. Correlations of Cl with cations and other anions, point to mixing with seawater. The isotopic composition of the thermal waters confirms the involvement of seawater. The thermal waters plot close to the global meteoric water line on a δ^2H versus $\delta^{18}O$ diagram. Linear correlations between δ^2H and Cl^- and $\delta^{18}O$ and Cl^- indicate mixture of meteoric and sea water.

Extreme interactions can also take place in low temperature systems if conditions are favourable. This is of great interest to geoscientists who tend to believe that low temperature geothermal is less reactive. The intense oxygen shift in a low temperature system was a surprising observation and is a good example of the value of isotopes in the study on water-rock interaction.

Geothermal waters from Tertiary aquifers, located at 1000 – 3000 m beneath Xi'an city, in Shaanxi Province, China, show unique isotopic composition compared to that of the local groundwater in shallower Quaternary aquifers. Positive oxygen shifts of as much as 8‰ VSMOW are observed, while the corresponding δ^2H values remain essentially constant at about -80‰ VSMOW. These values are significantly different from those of waters in the Quaternary aquifers with mean δ^2H value of -60‰ VSMOW. The large ^{18}O shift is a result of isotope exchange between geothermal water and carbonate minerals such as calcite, over a residence time of several thousand years to 30,000 years, based on ^{14}C dating. Waters in deeper aquifers probably have longer residence times, higher temperatures and lower flow rates than shallow groundwater.

A comparison of the isotopic composition of the Zhangzhou geothermal waters with water from the neighbouring Xianyang geothermal field, which is also situated in the Guanzhong Basin, indicates that the geothermal reservoirs are recharged by different sources. The pattern in their isotopic compositions is not as predicted according to the altitude effect principle, and further investigation is required.

5. TRACERS AND NUMERICAL MODELS

In order to develop sound geothermal reservoir management strategies, especially in re-injection design, various tracers have been used in geothermal development projects. However, the sensitivity of chemical tracers is not high enough for most of the reservoirs, which are low in permeability, e.g. in

the limestone formations.

Radiotracers I-125 and S-35 were used in doublet WR83 of Tianjin and obtained expected tracer returns that were not achieved by several runs of chemical tracer tests (Zhao, 2002).

6. CONCLUDING REMARKS AND FUTURE OUTLOOK

In the achievements described above, international education and research collaboration have played a key role in the development and application of novel technologies. For example, four fellows trained by the UNU-GTP throughout the years have made their respective contributions to the studies described. Further strengthening such training and cooperation will help to speed up the geothermal energy programme expansion in China, and elsewhere.

In order to reveal the details of geological structures of geothermal interest, hydrogeologists need to work more closely with geophysicists using advanced and effective prospecting tools, such as resistivity sounding (CSAMT) and seismicity, including micro natural vibration signals. With the help of geophysical prospecting tools, the chance of success in geothermal well siting will be improved.

Tracer test data analysis and water-rock interaction simulation in the re-injection scenario for geothermal reservoir management can be improved through wider use of coupled modelling by reactive transport numerical models such as TOUGHREACT.

Geothermal studies should be linked to new global efforts on sequestration of CO_2 in saline aquifers, to promote technical advances that would benefit both sectors. With this approach we will make full use of our knowledge of geothermal systems, not only for geothermal development, but to serve the mitigation on climate change.

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