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EDITORIAL

Progress and perspectives of geothermal energy studies in China: from shallow to deep systems

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In October 2015, the first Sino-German International Symposium on "Sustainable Utilization of Geothermal Energy" was held at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing, China. Around 120 researchers attended the meeting. It was agreed by the participants that a special issue of the papers presented at the symposium on Chinese geothermal systems be organized and published in the international journal "Environment Earth Sciences". Up to today, when we close the special issue, 30 papers have been accepted and published in this issue. From these papers one can find out the major progress made in geothermal energy studies in China in the past 5 years or so and, therefore, the papers provide a comprehensive overview of recent geothermal research in China.

According to the statistics published by the International Geothermal Association (IGA) in 2015, China had continued to lead the world in terms of total amount of geothermal used yearly for space heating and other direct use purposes. The present Thematic Issue covers studies on shallow geothermal energy (0–200 m), medium-deep hydrothermal energy (200–3000 m) as well as deep "hot dry rock" petrothermal energy (> 3000 m) in China. A prior introduction to studies on hydrothermal systems can be found in Kong et al. (2014). In the following we will highlight each of the papers in this Thematic Issue, and locations of study areas can be found in Fig. 1.

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Shallow geothermal energy

In the total installed capacity for space heating, shallow geothermal energy using heat pump technology takes up more than 50% of the total area being heated in China. Two papers in this issue discussed energy resource assessment methods based on results from thermal response tests, where they included the influence of groundwater flow. Zhang et al. (2016a) analyzed the influence of different groundwater flow conditions on the thermal response test in the Tangshan region in North China. Luo et al. (2018) determined ground thermal properties as relative to energy piles by thermal response tests.

Hydrothermal energy

Nine papers in this collection are focused on this type of geothermal resources, from exploration to reservoir engineering aspects. Xu et al. (2016) used classical and integrated multicomponent chemical geothermometry to estimate the reservoir temperature of the Tengchong geothermal field in Southwest China, which is the only high-temperature geothermal field related to modern volcanic activity in China. Geochemical workers now pay much attention to gaseous components in geothermal fluids in addition to aqueous components in the study of high-temperature geothermal systems in particular. These techniques have been used to evaluate the high-temperature Kangding geothermal system

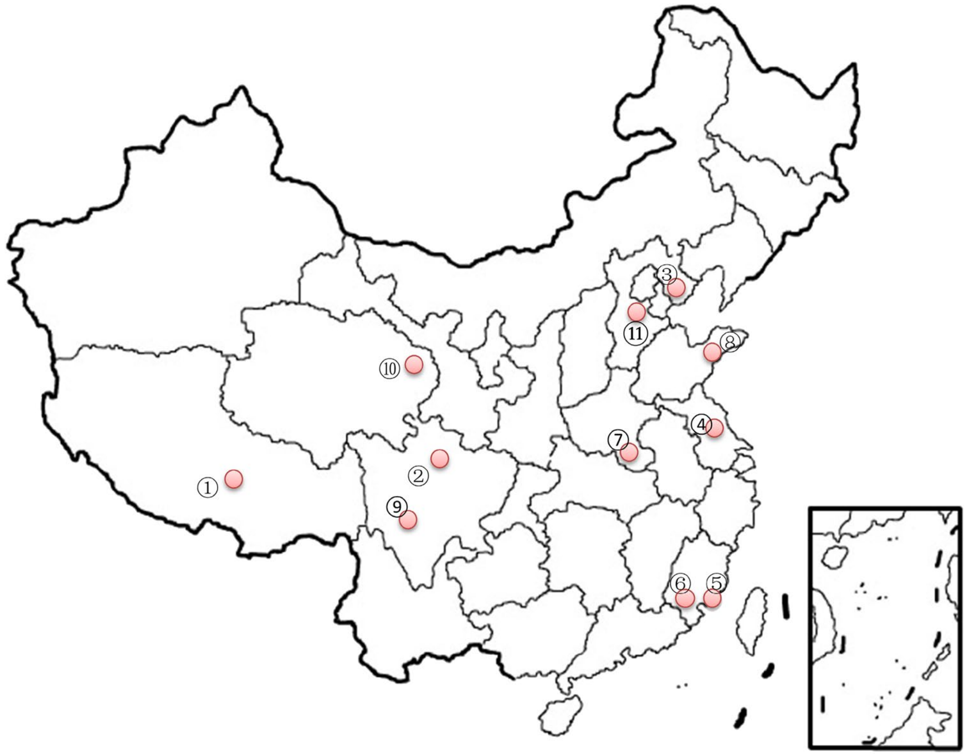

Fig. 1 Locations of study areas mentioned in the text. (1) Yangbajing, (2) Sichuan Basin, (3) Tangshan, (4) Jiangsu, (5) Xiamen, (6) Zhangzhou, (7) Xinyang (8) Shandong, (9) Kangding, (10) Zhacanggou, (11) Xiongxian

in western Sichuan Province of Southwest China (Luo et al. 2017). The gas geochemistry principles have also been applied to estimate reservoir temperature at great depth of the Bohai Bay Basin in North China (Pang et al. 2017a), where hot water from Karstic formations is being used in a large scale for space heating. Karst geothermics in China has attracted strong attention of researchers and developers home and abroad due to the great energy potential and easier production of carbonate reservoirs. Geophysical exploration on geothermal energy with new technology including the "Micro Tramer" has been introduced in this issue through a case study in Jiangsu Province of East China by Tian et al. (2016). Zhang et al. (2016b) carried out a 2-m survey method and its improved device as applied to Dongshan geothermal field in Xiamen of Southest China.

During the 12th national five-year plan (2010–2015), China completed a new round of nation-wide assessment of geothermal energy resources. Genesis analysis of geothermal systems has provided support to this effort. In this issue, Luo et al. (2017) conducted a geothermal potential evaluation and development prioritization based on geochemistry of geothermal waters from Kangding area, eastern syntax of Himalayan geothermal belt in western Sichuan, Southwest China, a place where high-temperature resources were found only recently. Tang et al. (2017) discussed the distribution and genesis of the same area in Southwest China. Wang et al. (2017) presented a review of geothermal energy resources and development in the Tibet Autonomous region. They reported that the exploitable geothermal resources is 1700.77×10^{13} J/a, equivalent to 51.19×10^{4} tons of standard coal, but the exploited amount of geothermal resources is mainly at a few places, such as Yangbajing geothermal field (Fig. 2) where a geothermal power plant has been operating for nearly 40 years, with an installed capacity of 25 MW. Other geothermal areas basically remain unexploited, so more needs to be done on utilization in the future.

Reservoir engineering is key to efficient and sustainable geothermal development. In Xiongxian county; geothermal resources from Karst reservoirs is being developed for space heating to a very large scale, up to 4.5 million m^2 using hot water from a single geothermal field, the largest in the world. 100% reinjection of used water has been achieved in this project and the coverage of space heating in the town is 95% by geothermal. It has been recognized by the Chiese government to be a model of success for hydrothermal resource development for space heating in North China. With the establishment of Xiongan New Area in 2017, which includes Xiongxian and two other counties, it is expected that the use of geothermal energy in this new area as well as North China will be further strengthened (Pang et al. 2017b). Kong et al. (2017a) studied optimization of well-doublet placement in geothermal reservoirs using numerical simulation and economic analysis. Co-axis down-hole heat exchanger is also an option when the permeability of the geothermal reservoir is not good enough for hot water extraction (Kong et al. 2017b).

Fig. 2 Geothermal power station in Yangbajing geothermal field (2006) (CC BY 2.5 license). *Source*: https://en.wikipedia.org/wiki/Geothermal_power_in_China

Hot dry rock geothermal energy

Utilization of geothermal resources below 3000 meters depth is generally rare in China. However, exploration and assessment for geothermal resources in the great depths is being carried out in the continent of China. In this issue, Jiang (2017) presented an estimate of potential for the continent of China based on an updated dataset of terrestrial heat flow, depth–temperature profiles, and provided the resource base for enhanced geothermal system (EGS) tests in the future. Lu et al. (2017) provided a review of genesis types of hot dry rock resources in China. Wang et al. (2016a) collected samples and analyzed radioactive heat-generation element contents on rock samples from Zhangzhou region, Southeast China, and their constraints on lithospheric heat production and thermal regime. Liu et al. (2017b) studied the thermal structure of Guide Basin to improve the understanding of hot dry rock energy potential in the region.

Enhanced geothermal systems (EGS) and related technology

Enhanced geothermal systems (EGS) technology has not been developed or tested so far in China. Papers in this collection show the progress of basic research on various issues related to EGS in China, mainly laboratory experiments and numerical modeling at field scale. Li et al. (2016) studied injection-induced fracturing process in tight sandstone under different saturation conditions. Bai et al. (2016) modeled local heat transfer characteristics of water flowing through a single fracture within a cylindrical granite specimen. Wei et al. (2016) modeled the hydromechanical responses of sandwich structure faults during underground fluid injection. Wang et al. (2017) analyzed shale gas hydraulic fracturing: a numerical investigation of the fracturing network evolution in the Silurian Longmaxi formation in the southeast of Sichuan Basin, Southwest China, using a coupled approach, which is relevant to geothermal development through EGS. Wang et al. (2016b) carried out a laboratory investigation of hydraulic fracture propagation using real-time ultrasonic measurement in shale formations with random natural fractures. Niu et al. (2017) conducted a numerical investigation on slippage characteristics of normal and reverse faults during fluid injection and production. Liu et al. (2017a) investigated the impact of CO_2 injection rate on heat extraction at Zhacanggou geothermal field, China. Compressed air energy storage (CAES) is a potential energy storage technology. A hypothetical case study with a short cycle period of injection and production was conducted to demonstrate the applicability of the developed solution in CAES. The results suggest that the semi-analytical solution is applicable for heat transfer in the wellbore of CAES (Li et al. 2017).

Methodological aspects, process models and geothermal data accumulation

Accquisition of deep temperature and thermal properties of different rock types has been a continued effort in geothermal energy studies in China. Ma et al. (2016) made down-hole temperature measurement using a 4000-m deep borehole and discussed its geothermal characteristics in Jiaodong Peninsula, China. Luo et al. (2018) determined the thermal conductivity of sandstones at laboratory and field scales. Liu et al. (2016) designed a multilevel U-tube sampler for subsurface environmental monitoring which is relevant to geothermal energy development from EGS sites. Huang et al. (2017) compared global and local implementations of nonlinear complementary problems for the modeling of multi-component two-phase flow with phase change phenomena. Yang et al. (2017) presented a numerical simulation of rock salt dissolution in dynamic water environments. Sun et al. (2017) carried out a fiber-optic monitoring of evaporation-induced axial strain of sandstone under ambient laboratory conditions. Jia et al. (2017) combined a connected-component labeling algorithm with FILTERSIM to simulate continuous discrete fracture networks. Xie et al. (2018) proposed a CO_2 mineralization approach for natural wollastonite into porous silica and $CaCO_3$ powders promoted via membrane electrolysis—an alternative for electricity production from carbon storage utilization.

New methods have been introduced into more realistic and efficient modeling of geothermal systems. Huang et al. (2017) introduced a novel method for non-isothermal multiphase multi-component flow simulation with phase change phenomena which allows for the analysis for different types of geothermal reservoir types with a consistent approach. For the analysis of fractured geothermal reservoirs various methods have been successfully applied such as lower-dimensional interface elements for finite element schemes (Watanabe et al. 2012) and the phase-field method (Tschukin et al. 2017). The latter allows also for a flexible simulation of the evolution of discontinuities in fractured geothermal systems. Systematic benchmarking procedures for geothermal analysis tools need to be developed, e.g. similar to related fields in geosciences (Kolditz et al. 2012).

Future perspectives on geothermal development in China

China is a country that is heavily affected by the dependency on fossil fuel for its fast economic development. Early last year, the central government launched a new plan—National Geothermal Utilization master plan for the 13th five-year plan that ends in 2020. It has set a very ambitious target for national geothermal energy development. By 2020, space heating will increase from 0.4 to 1.5 billion m^2; geothermal power generation will increase from 25 to 500 MW. This fast development of geothermal industry must be accompanied by enhanced research efforts. Geothermal development is expected to support the energy transition process from fossil to renewable geothermal resources and harmonization of energy with the environment. In order to foster the cooperation in geothermal research and utilization of geothermal energy resources, the Sino-German Geothermal Research Centre has been launched during the 1st Sino-German Symposium on "Sustainable Utilization of Geothermal Energy Resources" in 2015 in Beijing. During the past years the collaboration between the two countries, which includes joint research projects and exchange of scientists, has been deepened. Future joint academic events are being planned. The new journal "Geothermal Energy – Science, Society, Technology" offers not only an open access forum for discussion of various aspects of geothermal energy resources and technology including basic research, e.g. the characterization of deep geothermal systems, geothermal fluids in saline environments (Regenspurg and Schäfer 2017) or supercritical geothermal systems (Reinsch et al. 2017) but also socio-economic questions and aspects of technology implementation (Kolditz et al. 2017).

The Sino-German cooperation in geosciences has a long tradition. Other topics of Sino-German cooperation in geosciences have included, e.g. geological carbon dioxide storage and utilization as well as unconventional gas resources (Hou et al. 2015; Kolditz et al. 2015). The preceding volume "Subsurface Energy Storage I" dealt with geoscientific contributions to the energy transition in Germany (Kabuth et al. 2017; Bauer et al. 2012). We hope that the present Thematic Issue on "Subsurface Energy Storage II" will achieve the goal of highlighting the results of collaborative geothermal energy research in China by Chinese and German scientists and will stimulate new ideas for future collaboration.

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