The Special Issue on Hot Dry Rock Resource Exploration and Enhanced Geothermal Engineering

Preface

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Geothermal energy is used worldwide primarily for generating electricity, space heating and spas. The geothermal resources that have been developed, however, produce only a small fraction of the available energy stored in the upper few kilometers of the earth’s crust (Tester et al., 2006). Although heat is present, rocks throughout most of the shallow crust lack the interconnected permeability necessary to form geothermal reservoirs. Attempts to create permeability by hydraulic fracturing were first conducted in the 1970s at Fenton Hill, New Mexico, USA (Wyborn, 2011). More than a dozen Enhanced Geothermal System (EGS) projects followed in Great Britain, France, Japan, USA, Australia, Switzerland, South Korea, and China (Tester et al., 2006; Breede et al., 2013; Olasolo et al., 2016) (Fig. 1). Despite seismic evidence that large volumes of rock were stimulated, subeconomic flow rates and low thermal recoveries indicate that the fractures were poorly connected (Grant, 2016). Furthermore, temperature and drilling data suggest that the primary fluid conduits were preexisting fractures (Fig. 2). Although none of the projects demonstrated full commercial viability of EGS, they did underscore the need for specific technological advances. These include: 1) geoscientific and rock property characteristics of EGS resources; 2) evaluation of in-situ fracture networks and stress fields; 3) improved high temperature directional drilling technologies; 4) novel zonal isolation tools and reservoir stimulation technologies; 5) high-temperature tools for seismic monitoring of reservoir growth and prediction of induced seismicity; and 6) power conversion technologies (Feng et al., 2014; Lu, 2018; Moore et al., 2021).

EGS research was initiated in China in 2012. Laboratory facilities were designed and constructed to understand the processes occurring during reservoir stimulation, including coupled hydraulic-mechanical processes under step-wise injection pressures and high stress and temperature (Zhang et al., 2019; Shu et al., 2020; Cheng et al., 2021). Effects of joint hydraulic-thermal-chemical stimulations (Chen et al., 2017; Rong et al., 2021), and hydrothermal flow in fractured rocks were investigated (Bai et al., 2017; Rong et al., 2018; Huang et al., 2019). Advanced numerical programs including TOUGH2Biot and TOUGH-EGS were developed to incorporate mechanical processes. The application of these simulations assisted in developing new approaches for reservoir stimulation in crystalline rocks (Hu et al., 2013; Lei et al., 2015; Jiang et al., 2019).

Beginning in 2016, new funding was provided by the Ministry of Science and Technology of the People’s Republic of China, the China Geology Survey, and private organizations for numerical modeling of fracture behavior, drilling technologies and characterization of potential EGS demonstration sites. A location in the Gonghe Basin in northwest China was selected. The first deep well, GR1, encountered a temperature of 236°C at a depth of 3700 m in low permeability granitic basement rocks.

Interdisciplinary research has significantly advanced our understanding of the spatial distribution of EGS resources, hydraulic fracturing and induced seismicity. This knowledge can be applied to a broad range of EGS environments ranging from high-temperature resources for electric power generation to low-to-moderate temperature resources for space heating and other direct use applications.

This special issue of Acta Geologica Sinica (English Edition) includes sixteen papers describing the results of recent research on EGS in China and the lessons learned. The research covers a broad range of topics including geological and geophysical techniques for exploration and characterization of EGS resources, hydraulic and chemical stimulation for permeability enhancement, seismicity monitoring and interpretation, novel multi-physics modeling and simulation, and utilization of EGS resources. It is our hope this body of work will be of interest not only to those active in EGS development but also to the broader community of scientists, engineers and graduate students interested in heat and fluid flow within the earth’s crust.

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The collection and interpretation of geological, geophysical and geochemical data represents the first step in the characterization of EGS resources. These data provide the foundation for sustainable geothermal energy development and utilization. They also provide essential information for the advanced numerical tools needed to provide insight into hydrothermal processes in deep reservoirs. Lin et al. (2021-this issue) mapped the 3D thermal structure of the Gonghe Basin by integrating lithofacies distributions interpreted from seismic surveys, high-precision heat flow calculations using temperature data from nine drillholes up to 3500 m depth, and measurements of thermal conductivity and radioactive element contents. It was found that crustal thickening enhances crustal heat flow but hampers mantle heat flow in the basin. The structure of the basin was further characterized by Wang et al. (2021-this issue), based on interpretation of gravity and seismic data and magnetic anomalies. Yu et al. (2021-this issue) investigated hydrothermal processes occurring in the Roosevelt Hot Springs geothermal field in Utah, USA by integrating geological and geochemical data with numerical simulations of flow, heat and chemical transport. Kong et al. (2021-this issue) proposed that the type of heat source is a more robust criterion, in comparison to temperature, for locating sites suitable for EGS development. Areas of high heat flow (>100 mW/m²) with mantle-derived magma heat sources are highlighted for EGS reservoir creation following a critical review of the geology and geochemistry of EGS sites worldwide. One benefit of the advancements in geophysical prospecting and computational techniques was an increase in the number of potential EGS resources in China. For example, Kang et al. (2021-this issue) described the geological and thermal conditions of hot dry rocks in the Linqing Depression, Shangdong, China. They concluded that once EGS is established, hot fluids circulating through karstified carbonate rocks at 8000 m depth have the potential to generate approximately 3000 MWe of electric power.

The creation of EGS reservoirs suitable for long-term energy extraction requires fracture creation or enhancement by hydraulic stimulation. However, past...
attempts to create EGS reservoirs consisting of interconnected fracture networks has proven challenging, irrespective of the stress regime. Both fracture theory and stimulation technologies are still immature relative to those implemented in oil/gas shales. It is now widely accepted that the geometry of the stimulated region is strongly dependent on the initial fracture geometry, local and regional stress distributions and magnitudes, and the operational parameters employed during the hydraulic stimulations. Wang et al. (2021-this issue) proposed a methodology for fracture characterization based on downhole image logs. This approach was implemented in the Rongcheng Geothermal Field, where the fracture density was estimated at 9–15 per 100 m at depths ranging from 3000 to 3500 m. Xie et al. (2021-this issue) systematically tested the response of different discontinuities, including fractures, veins and lithologic interfaces to hydraulic stimulation. They found that these discontinuities have a major influence on the development of the hydraulic fractures. Xie et al. (2021-this issue) also found that varying the injection pressures increased the complexity of the fracture pattern. Liu et al. (2021-this issue) investigated fracture geometries at different scales and permeabilities under injection rates ranging from 3 mL/min to 7 mL/min and confining pressures of 5 MPa to 30 MPa. In addition, the effects of chemical stimulation with both acid and alkaline fluids on fracture development were compared. Novel acid stimulants composed of 2.5mol/L HCl+0.5 mol/L were shown to enhance the permeability of fractures in hot granites (Xu et al., 2021-this issue). Moreover, Chen et al. (2021-this issue) proposed a methodology for fracture creation in low permeability rocks based on laboratory experiments, numerical modeling and field tests. The method consists of first injecting cool fluid to create and stimulate fractures near the injection well, followed by high-pressure injection with stepwise and cyclic injection rates. It was also found that gel had a greater effect on fracture enlargement and width than water.

Real-time seismic monitoring during hydraulic fracturing is a critical tool in EGS reservoir construction and currently is the most effective means of determining the size, shape and growth of the fractured volume and the potential for induced seismicity. Sun et al. (2021-this issue) developed a novel machine learning model that allows fast and accurate seismic event detection by combining gated recurrent neural network and support vector machines. Chen et al. (2021-this issue) established a correlation between hydraulic parameters and induced seismicity, based on observations from the EGS-demonstration project site in the Gonghe Basin.

Song et al. (2021-this issue) developed a multi-object optimization algorithm by integrating a linear regression, non-dominated sorting genetic model with a coupled flow and heat transport model. The model was utilized to optimize well locations and injection and extraction rates for EGS development at the Gonghe Basin site.

Organic Rankine cycle (ORC) power plants are widely used for geothermal electric generation, particularly at low-to-moderate temperatures up to about 200°C. Li et al. (2021-this issue) investigated the impacts of dryness and non-condensible gas contents on power generation, and find that the performance of ORC systems were overestimated without considering these parameters. Yu et al. (2021-this issue) proposed a triple-stage ORC system that provided superior thermodynamic and economic performance compared to single and double stage systems. Further improvements were achieved by optimizing the working fluid based on the inlet temperature. R601a (isopentane) was recommended for temperatures below 145°C, R245fa for temperatures between 145°C and 185°C, and R600a (isobutene) for temperatures between 185°C and 200°C. Wang et al. (2021-this issue) established a comprehensive model that combined the temperature decay in the reservoir, energy loss in the wellbore, and thermal efficiency of the surface equipment to compare the performance of a pure ORC power generation system with a combined-heating-and-power (CHP) system. It was concluded that the Levelized Cost of Electricity (LCOE) of the CHP system is 35% less compared to the ORC system. Consideration of carbon emission trading prices further reduces the LCOE of the CHP system by an additional 8.5%. Based on these calculations, it was concluded the CHP system has significant economic advantages over ORC systems for power generation from EGS resources.

It is predictable that hot, low permeability rocks will contribute significantly to carbon emission reductions while providing an environmentally benign and inexhaustible source of energy for electric generation and direct uses. However, significant challenges must be overcome to economically extract and utilize this energy. The EGS demonstration project in the Gonghe Basin represents an important step in the development of these resources. The papers in this special issue describe the challenges and research results in five crucial areas of EGS development: resource exploration, reservoir stimulation, reservoir characterization, well placement optimization, and geothermal energy utilization. We hope these contributions provide a useful overview of progress on EGS as well as the critical problems that must be solved in the future to achieve commercial viability of this vast, untapped resource.

References


