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Development Strategy for Co-mining of the Deep Mineral and Geothermal Resources

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Abstract: The co-mining of deep minerals and geothermal resources (hereinafter referred to as "co-mining") is an important measure to achieve the sustainable development of deep mining and provides a new technical means for geothermal mining in deep high-temperature rock strata. This study analyzes the importance of co-mining, reviews the current situation of the exploitation and utilization of geothermal resources in China and abroad, and summarizes the basic research progress in co-mining in China. Based on an analysis of the technical and management challenges faced by co-mining, this study develops a technical system that is urgently needed for the comprehensive exploitation and utilization of geothermal resources. This system involves the investigation and prospect study of the exploitation and utilization of deep mineral and geothermal resources, the construction of underground roadways and chambers in high-temperature hard rock strata, the key theories and technologies of "coconstruction–coexistence–co-use" of deep mineral resources exploitation system and geothermal development system, and the theories and technologies for the exchange and transport of geothermal energy in deep high-temperature rock strata. This study proposes development suggestions for geological exploration, scientific and technological innovation, supportive policies, top-level planning, and the basis of scientific research demonstrations, to provide references for the sustainable and high-quality development of China's mining and geothermal industries.
Keywords: deep minerals; geothermal resources; co-mining of deep minerals and geothermal resources; high-temperature rock strata; geothermal energy exchange and transport

1 Introduction

After years of large-scale continuous mining, China's shallow mineral resources have gradually decreased and are being depleted year by year, and the mining of mineral resources, especially metallic resources, has gradually advanced to greater depths [1]. A number of metal mines have reached or exceeded a mining depth of 1 km, and almost all of the large- and medium-sized metal mines being built or planned are deep underground mines. In the next ten years, more than 1/3 of the metal mines in China could reach or exceed a depth of 1 km, and some of them

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could reach 2–3 km [2,3]. Therefore, deep mining is the most important way to ensure the sustainable development and supply of metallic resources in China [4–6].

Deep metal mines face a series of key problems, with the most prominent issue being the high-temperature environmental conditions that make deep mining difficult to sustain [3,7]. To maintain normal production, cooling treatment is necessary. Common cooling techniques are divided into nonartificial cooling and artificial cooling. Mine ventilation is the main nonartificial cooling technology. However, when the shaft depth exceeds 1 km, conventional ventilation cannot meet the cooling requirements, and it must be supplemented with artificial cooling. Two types of artificial cooling, i.e., water cooling and ice cooling, are available. In water cooling systems, ground air conditioning systems are applied to cool underground mines. As early as the 1960s, South Africa began to use large-scale central air conditioning systems in mines; however, as the depth of a mine increases, water cooling systems inevitably suffer from high hydrostatic pressures and intractable condensing heat discharge. Ice cooling systems use the latent heat of ice melting for cooling, and the water amount required to obtain the same cooling capacity is much lower than that of water cooling systems [8]. In the early 1980s, countries such as South Africa began to research and apply ice cooling systems. After the well depth exceeds 2–3 km, the cost of artificial cooling can be very high and unaffordable for most mines. It should also be noted that existing cooling technologies rely on passive cooling; active cooling technologies must be developed and applied to solve the problem of high mining costs caused by passive cooling.

The most promising development in active deep well cooling technology is the use of deep geothermal energy [9]. In fact, the high-temperature environment of deep wells is mainly caused by the thermal radiation of high-temperature rock strata, which is due to geothermal energy, a natural clean energy source. The use of heat exchange technology in deep mining is a way of developing and utilizing deep geothermal resources in a combined manner. The exploitation of deep geothermal resources can not only change a “thermal hazard” into a “thermal benefit” and create conditions for cooling the underground mining environment but also greatly reduce costs through the adoption of a series of passive measures specifically for cooling the mining area, which are expected to provide a novel disruptive, technoeconomic approach for cooling deep wells. Previous studies have proposed an enhanced geothermal system (EGS)-based excavation technology (EGS-E) and specifically described the system principles, engineering concepts, and technical advantages of this system [10–12].

Based on a comprehensive investigation of the geothermal occurrence in deep high-temperature rock strata in China and the types and characteristics of areas where minerals and geothermal resources co-occur, this study analyzes the current situation of deep geothermal exploitation and utilization in China and abroad, summarizes the important research progress in related fields in China, proposes a technically and economically feasible win-win strategy for the co-mining of deep mineral and geothermal resources (hereinafter referred to as “co-mining”), analyzes the key issues and technical bottlenecks in the joint exploitation and utilization of deep minerals and geothermal resources, clarifies the key research tasks of co-mining, and proposes targeted development suggestions to promote the implementation of the co-mining strategy. Relevant research results can provide a forward-looking path and strategic inspiration for the medium- and long-term sustainable development of resources and energy in China.

2 The significance of the co-mining of deep minerals and geothermal resources

2.1 Co-mining is an important trend in the comprehensive exploitation and utilization of natural resources.

The large-scale exploitation and utilization of natural resources that have lasted for thousands of years has broken the balance of Earth’s ecosystems, leading to frequent climate changes and extreme climate events and posing serious challenges to human survival and development. Global climate control has become a major issue for countries around the world. China’s carbon peak and carbon neutrality goals reflect the responsibility of promoting the construction of a community with a shared future for humankind and are an inherent requirement for achieving sustainable and high-quality development. Although to achieve the carbon peak and carbon neutrality goals on time, the use of fossil energy such as coal may gradually decrease or disappear, the demand for energy for economic and social development will continue. As a green, low-carbon, nonpolluting renewable energy source, geothermal energy has immense storage capacity and is a powerful option to replace traditional fossil energy and meet ever-increasing energy demands. Deep mineral resources and geothermal resources may be an important factor in promoting China’s energy transformation and profound changes in the global energy and resource supply pattern, which are conducive to the development of the national economy in the direction of high efficiency, environmental

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protection, cleanliness, and low carbon. These changes are also important to guaranteeing the human demand for a beautiful ecological environment and a good life.

From the mesolevel perspective of the sustainable development of deep mining, it is not economically feasible to use existing technology to mine mineral resources at depths of 2 km or more due to the excessively high cooling costs. Co-mining can not only significantly reduce the cost of traditional passive cooling but also improve the comprehensive mining benefits of minerals and geothermal resources. Co-mining provides a new model and a new path to solve the economic problem of high cost and low benefit for deep mining while enabling the sustainable and large-scale development of deep minerals.

2.2 Co-mining provides a new technical means for geothermal mining in deep high-temperature rock strata.

The vast majority of geothermal energy is stored in the high-temperature hard rock strata at depths of 3–10 km. With the increasing demand for geothermal energy, the importance of and reliance on the exploitation and utilization of geothermal energy are rapidly increasing in various countries. Traditional methods such as oil drilling have problems in exploiting deep geothermal resources, such as a high difficulty and a low capacity, while EGS technology faces many difficulties related to the construction of artificial thermal storage. (1) The geothermal exploitation systems used at depths of 3–10 km below the surface require special technologies and equipment (adapted to high-temperature hard rock strata and high geostress conditions) to construct special rock projects, structures, and channels and maintain their stability, which is unprecedented and extremely difficult. (2) Due to the high geostresses at great depths, the fractures created by hydraulic fracturing often close, resulting in disconnections or short circuits between fractures, which makes it impossible to build and maintain a sufficient volume of heat reservoirs. (3) For existing fractures under multiple high-pressure excitations, direct connections between production wells and injection wells may occur, giving rise to the fluid short-circuiting effect [13], which leads to a complete loss of the heat exchange effect. (4) When an EGS is used to exploit geothermal energy, the water circulation process of the water injection wells and production wells often consumes a large amount of water, which may cause environmental problems related to groundwater. To date, no effective solution has been developed for the utilization of deep geothermal energy using EGS technologies, the relevant work is still in the research and experimental stage, and there is a considerable gap between the research and large-scale industrial applications [9].

The application of mining technology in geothermal mining can effectively solve the abovementioned problems of the EGS. The mining depth of hard rock mines has exceeded 4 km, and deep excavation technology is very mature. The use of mining technology, the excavation of shafts from the ground surface to the deep high-temperature rock strata, the excavation of multiple horizontally distributed roadways in the lower part of the shafts, and the fracture network formed in the ore body by blasting can significantly improve the thermal storage construction capacity, increase the heat exchange area and the magnitude of geothermal energy acquired and outputted, creating favorable conditions for large-scale geothermal exploitation. Excavated shafts and roadways can be co-used for mining operations and geothermal exploitation to minimize environmental pollution while reducing the cost of geothermal exploitation. Therefore, the application of co-mining technology is likely to provide a new technical means for future geothermal mining in deep high-temperature rock strata.

3 The current situation of the exploitation and utilization of deep mineral and geothermal resources and the scientific and technological basis of co-mining in China

3.1 Exploitation and utilization of geothermal resources in deep high-temperature rock strata abroad

For geothermal exploitation in deep high-temperature rock strata, EGS technologies have been studied abroad for over 50 years. Holes are drilled into deep high-temperature rock strata using the method of oil exploration drilling, and downhole operations such as hydraulic fracturing are applied to create a fracture system with a high permeability in the hot dry rock at the bottom of the borehole, thereby “artificially” creating a geothermal reservoir (thermal storage); cold water is injected into the heat reservoir from the injection well (one or several wells) on the surface and then pumped out to the surface from the production well (several other wells) after heat exchange in the fractures; the generated geothermal steam is used for thermal energy applications such as power generation.

Research on the exploitation of geothermal resources using the EGS increased in the 1970s and 1990s. Six field test projects were successively carried out in the United States, the United Kingdom, Japan, and France. In 1973, the first EGS field test was conducted in Fenton Hill, New Mexico, followed by a test in Geysers, California. The period from 1991 to 2000 was a low-tide period for the study of hot dry rocks, and no new EGS projects were implemented.

Since 2001, research on hot dry rock has once again increased. The United States, Germany, Australia, and South Korea have launched a number of EGS research and field test projects. As of 2019, 14 countries in Europe, North America, Australia, Asia, and Central America have implemented a total of approximately 41 geothermal resource exploration and development projects in deep high-temperature rock strata, of which 25 are traditional geothermal systems and 16 are EGS [14]. The Sulz hot dry rock project in France, jointly developed by France, Germany, and the United Kingdom, with a small installed capacity (1.5 MW), has been in operation for over 30 years, but it is not continuously operated.

3.2 Exploitation and utilization of geothermal resources in China

According to the occurrence depth and temperature, the geothermal resources in China are mainly categorized into shallow geothermal, hydrothermal, and dry-hot rock types. Shallow geothermal resources (depth < 200 m, temperature < 90 °C) can be found all over the country, the energy is 9.5×10^{9} tce, and the available resources are 7×10^{8} t/a. Hydrothermal resources (medium and deep rock strata with a moderate temperature of 90–150 °C and a depth of 200–3000 m) are concentrated in the large sedimentary basins, the energy is approximately 1.25×10^{12} tce, and the main types of geothermal resources under exploitation and utilization are hydrothermal resources with a shallow depth of 200 m. The development potential of dry-hot rock geothermal resources (a depth of 3–10 km and a temperature of 150–650℃) is 100–1000 times that of shallow geothermal resources, and the amount of geothermal energy resources in deep high-temperature rock strata in China is approximately 8.6×10^{14} tce [4]. Dry-hot rock geothermal resources are considered to be one of the best alternative energy sources in the future, and China is also committed to their efficient exploitation and utilization.

In China, the exploitation and utilization of hot spring resources have a history of more than a thousand years, but the large-scale implementation of geothermal exploration and utilization has mostly occurred in recent decades. In the 1950s, the large-scale utilization of hot springs began, followed by a diversified exploitation and utilization pattern of geothermal energy represented by hot spring bathing, health care, heating, and power generation. After 2000, driven by national support and market demand, the exploration and utilization of geothermal resources entered the fast lane of development [15]. The direct utilization of hydrothermal energy has continued to grow at an average annual rate of 10%, ranking first in the world for many years. The installed power generation capacity was 27.28 MW in 2017, 44.98 MW in 2018, and 49.1 MW in 2019 [15,16]. For shallow geothermal energy, the installed capacity of ground-source heat pumps in 2017 was 2×10^{4} MW, and the heated building area was 5×10^{8} m^2 [16].

It should be noted that although the exploitation and utilization of medium and shallow geothermal resources in China have been developing rapidly, their proportion in the national primary energy consumption is very low (approximately 0.5%). Therefore, it is necessary to continue to strengthen geothermal mining in deep high-temperature rock strata. Research on the development of geothermal energy in deep high-temperature rock strata in China is in its infancy, and relevant exploration and research initiatives only begin in the early 21st century. In 2017, high-temperature dry hot rocks (a temperature of 236 °C) were drilled at a depth of 3705 m in the Gonghe Basin of Qinghai Province, but no field tests of the development potential of geothermal energy using the EGS were conducted. Overall, the development of geothermal energy in deep high-temperature rock strata in China is still in the field test stage, and information from the development of petroleum engineering is mostly used to explore the development prospects; there are many urgent technical bottlenecks in geological screening models and high-temperature drilling and completion processes, and a complete EGS development evaluation system has not been created [17].

3.3 Research progress on co-mining in China

3.3.1 Resource strategy and exploration

This study concludes that China is in a favorable geotectonic position related to global mineralization. China is located at the intersection of the Eurasian plate, the Indian plate, and the Pacific plate. Due to the subduction and collision of the three plates with the Chinese plate, a series of large and superlarge deposits have been formed. The mineralization conditions in China are superior, and the mineral types are complete, with obvious zoning, grouping, and regular distributions.

Four geological types for the exploration of deep geothermal resources in China are proposed: the high radioactive heat generation type (southeast coastal area), the sedimentary basin type (the lower part of Cretaceous basins in Guanzhong, Xianyang, Guide, Gonghe, and Northeast China), the modern volcano type (Tengchong, Changbai Mountain, Wudalianchi, etc.), and the intraplate active tectonic belt type (Qinghai-Tibet Plateau).

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By studying the distribution of large and ultra large metal deposits and geothermal resources in China, Jiaodong, the middle and lower reaches of the Yangtze River, the eastern Qinling Mountains, and northwestern Yunnan have been determined to be common co-occurrence areas of geothermal and mineral resources, with enormous potential for co-mining. Considering factors such as the topography, development cost, and actual demand, exploratory co-mining projects in the Jiaodong area, including Sanshan Island, Xincheng, Jinqingding, and Linglong Gold Mine, are advisable.

3.3.2 High-temperature underground engineering technology system

Under high-temperature conditions, the rock properties, surrounding rock deformation mechanism and control technology, working face cooling technology, stratum modification materials and technology, excavation equipment applicability and development direction, and mine roadway construction mode for the co-mining of geothermal and mineral resources have been studied, and a development approach for the co-mining of underground minerals and geothermal resources has been proposed. In addition, the properties of the high-temperature rock, the drillability and feasibility of mechanical rock-breaking drilling in shafts, the heat insulation of high-temperature rock strata, and the rock modification processes and materials have been obtained.

A technical system including the basic theories, key technologies, excavation equipment, engineering materials, and construction process has been developed for the excavation and construction of underground high-temperature hard rock tunnels and caverns. A mechanical rock-breaking shaft construction equipment system and an unmanned robot construction model has been proposed; the rock support technology, structure and materials for deep wells in high-temperature rock strata and stability control technology of rock support, stratum modification, stress control, and section optimization for deep wells have been developed; three types of engineering development and lifting modes, i.e., vertical shaft + inclined shaft lifting, vertical shaft U-shaped structural fluid lifting, and slope spiral graded lifting, and the well–roadway–hole joint layout geothermal exploitation mode based on the U/L/Q type + 360° drilling type, have been constructed.

3.3.3 The theory and technology of co-mining

Mining facilities, an engineering layout, and a development sequence based on the principle of coconstruction–coexistence–co-use, which are suitable for the three mining types of block caving mining, cut-and-fill mining, and in situ leaching mining and applicable to the co-mining of mineral and geothermal resources, have been proposed. Experimental studies on the effects of temperature and chemical field changes on the mechanical properties of granite have been conducted, and the mechanical properties of the thermal and chemical damage induced by thermal extraction during co-mining were summarized.

The current situation of the exploitation and utilization of geothermal resources with the development of metal mines, coal mines, and salt mines was investigated, and the methods and technologies used in the practice of co-mining were identified through case studies. Aiming at the environmental identification of co-mining target areas, the integrated exploration technology of mineral and geothermal resources was analyzed, and the mechanism of coupling between mineral exploitation in a high-temperature environment and multiple fields, such as stress, seepage, and chemistry, was explored.

3.3.4 Research on deep geothermal energy exchange and transport

A high-medium-low multitemperature hierarchical thermal energy extraction system for co-mining has been proposed; the thermal energy exchange, extraction and transport systems for hot and cold masses at different temperatures and the co-mining process in the medium temperature zone have been developed; measures were proposed to extend the effective ventilation distance, prevent underground thermal damage, and reduce the energy loss of heat storage by using the thermal insulation layer and optimized parameters during construction.

The theory and technology of high-temperature and high-pressure thermal energy transport suitable for co-mining have been proposed. The thermal energy transport mechanism and supporting technology system of high-temperature, high-pressure fracture flow and pipeline flow have been established, the transport capacity and efficiency of different transport technologies have been analyzed, and the generation of random fractures in thermal storage by enhancement techniques has been proposed as an effective method to enhance the efficiency of thermal energy extraction. The important conclusion that the heat transfer in fractures is better than that in the pipe flow in the fracture heat transfer area was obtained through simulations.

4 Challenges, development framework, and key tasks for the co-mining of deep minerals and geothermal resources

4.1 Challenges faced by the co-mining in China

4.1.1 Low degree of exploration in areas where metallic resources and geothermal resources coexist

The exploration and evaluation of the co-occurrence of metallic resources and geothermal resources in China have just started, and the actual quantity of these resources is unclear. Investigation and research on the distribution, types, and reserves of metal deposits and geothermal resources and the correlation between the two types of resources are still inadequate. The prospective areas, favorable areas, target areas, and mining areas for co-mining must be further investigated. For the exploration of deep high-temperature geothermal resources, reliable resource evaluation technologies and methodologies have not been developed, and there is an urgent need to expand high-tech applications and reoptimize survey techniques. These aspects are the bottlenecks restricting co-mining in China.

4.1.2 Weak basic research on the joint exploitation and utilization of deep minerals and geothermal resources

Co-mining was first proposed in China. No precedent has been established elsewhere in the world, and the relevant research and implementation require interdisciplinary and multidisciplinary systems engineering. The related basic research is extremely weak, and the research in many related fields is lacking; thus, innovative, interdisciplinary, systematic, and continuous research is needed. Fundamental research issues mainly include accurately prospecting and predicting the location, concentration, and distribution characteristics of geothermal energy in mining areas; the use of existing or innovative geothermal development theories and technologies for geothermal exploitation in mining areas; the safe and effective excavation of shafts, roadways, and chambers in deep, hot, and hard rock strata; the construction of mineral resource excavation systems and geothermal development systems (e.g., thermal storage) in deep, high-geostress rock strata to achieve coconstruction–coexistence–co-use; screening heat exchange systems and technologies to extract the geothermal energy resources stored in deep, high-temperature rock strata and transport them safely and economically to the surface and other suitable places for later use; and confirming the adaptability of exchange systems and technologies for various types of geothermal sources. In addition, there is a gap between China’s deep high-temperature rock geothermal drilling technology and the advanced technology available elsewhere in the world. Further, technical research on geothermal exploration and development in high-temperature rock, the comprehensive utilization of geothermal resources in a graded manner, geothermal recharge and anticorrosion and antiscaling technologies as failed to make breakthrough progress and meet the actual demand.

4.1.3 Industry planning and policy measures must be improved

Some of the current fiscal and price incentive policies in China have played a positive role in accelerating the development and clean utilization of geothermal resources, but no policy support for the emerging direction of the co-mining, exploitation and utilization of minerals and geothermal resources has been developed. Further, specialized industry plans, technical standards, and management methods have yet to be formulated. Due to policy lag, the operability of the relevant fiscal and taxation laws and regulations is poor, the actual implementation is not ideal, the necessary incentive measures are inadequate, and the targeted support policies must be strengthened [18]. It is worth noting that at this stage, China’s dependence on fossil fuels such as oil and gas remains high, and there is an urgent need to strengthen the exploitation and utilization of alternative energy sources and enrich the technical reserves in the mid-to-long term; the use of geothermal energy must catch up with the pace of advanced countries, and the shortage of high-end compound talents and the lack of specialized innovation development platforms directly restrict the high-quality development of the geothermal industry.

4.2 Development framework for the co-mining of deep minerals and geothermal resources in China

Investigating the current situation of the exploration, exploitation and utilization of deep geothermal resources in China and analyzing the distribution and characteristics of deep mineral resources and deep geothermal coexistence areas can provide basic support for the formulation of policies by the relevant national departments and the research and development in related fields. Existing mining technologies for deep mineral resources and the exploitation and utilization of deep geothermal resources should be systematically reviewed, and multidisciplinary systematic in-depth research should be conducted to construct an engineering framework for co-mining, which is both practical and economical (Fig. 1) and covers key technologies, such as geothermal and mineral resource exploration, excavation and construction, mineral and geothermal exploitation, and geothermal utilization.

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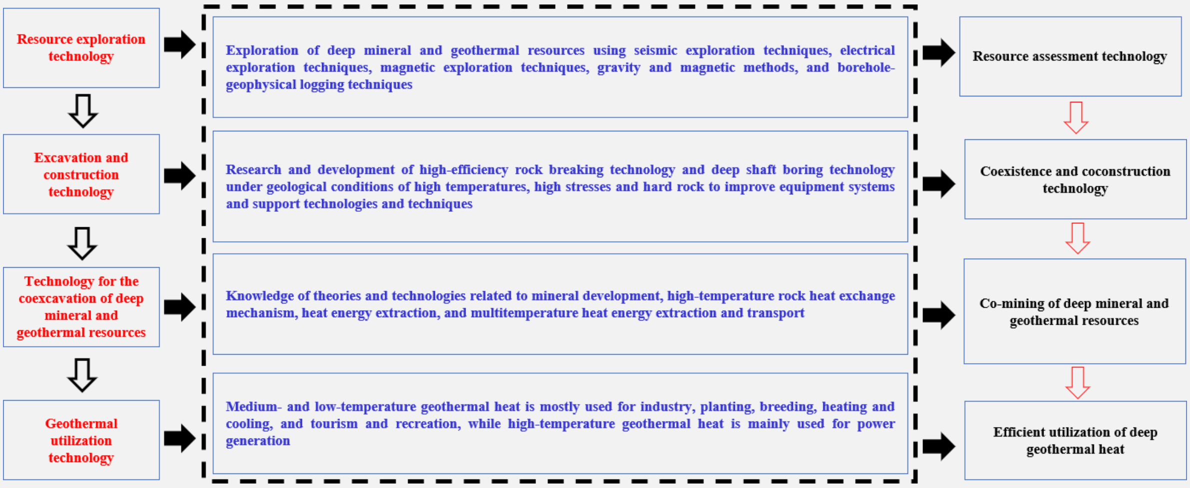

Fig. 1. Engineering framework for the co-mining of deep mineral resources and geothermal resources.

To support the implementation of the above engineering framework, the following aspects should be promoted: (1) The technical progress in the exploitation and utilization of deep mineral and geothermal resources should continue to be tracked, and the main technology roadmaps should be evaluated to propose a development roadmap for China's future technology. (2) Based on the current status and existing problems of the co-mining and utilization of deep mineral and geothermal resources in China, the technical, institutional, and mechanism bottlenecks that restrict the co-mining and utilization of these resources should be analyzed, and a suitable macro plan for the development of the co-mining and utilization of these resources in China is needed. (3) Studies of the relevant policies and regulations related to the co-mining and utilization of deep mineral and geothermal resources in China and abroad are needed, as is the development of policy recommendations to promote the implementation of these approaches by enterprises, including incentives for applying new technologies, industrial policies, environmental protection regulations, and fiscal and tax policies.

4.3 Key research directions for the co-mining of deep minerals and geothermal resources in China

4.3.1 Investigation of the occurrence, exploitation, and utilization of deep geothermal resources and analysis of the prospect of joint exploitation and utilization of deep mineral resources and deep geothermal resources

Data and information must be collected to grasp the new achievements and progress in the exploration, development, and theoretical research of deep geothermal resources worldwide. It is necessary to further investigate and study the distribution, development, technological development trends and core issues of deep geothermal resources in China. On the basis of comprehensively tracking international progress and understanding the occurrence and development in China, a comparative study of deep geothermal resources in China and abroad should be conducted to provide a solid foundation for research on the exploration and development strategy of deep geothermal resources in China.

In-depth research on the distribution of deep geothermal and mineral resources in China should be conducted, and the geological characteristics of the areas where metallic resources and geothermal resources co-occur should be first investigated. For example, in the Huize area of Yunnan, the Qinling area of Henan, and the Jiaodong Peninsula, the temperature of the rock layer at a depth of 500 m in some mines exceeds 40 °C, and artificial cooling is needed year round, indicating potential targets for co-mining.

The technical efficiency of co-mining should be further studied, and the effective methods of using the vertical shafts, inclined shafts, and roadways in mining systems to simultaneously exploit geothermal energy should be explored to combine temperature control in deep mine operations and the development of clean geothermal energy. The target areas of co-mining in China's mineral resource-rich provinces are proposed in detail to clarify the main direction for further technological research and development.

4.3.2. Excavation and construction of underground roadways and chambers in high-temperature hard rock strata

The distribution pattern and anomalous coupling characteristics of the temperature field-stress field-seepage field in deep high-temperature hard rock should be determined. The rock mass structure, thermodynamic characteristics and variability of deep high-temperature rocks and soils under long-term high temperatures and temperature changes need to be analyzed, and the detection technology of related physical fields studied. The coupling mechanism of the temperature field–stress field–seepage field in deep high-temperature hard rock strata and the inversion analysis methods should be analyzed to predict the safety and durability of geothermal mining and storage. The high-efficiency matching relationship between phase change energy storage materials with different thermophysical properties (phase change temperature, latent heat, and heat capacity) and deep geothermal temperature should be analyzed to clarify the heat exchange mechanism.

The overall planning, engineering design, and process suitability of shaft (chamber) projects in deep high-temperature hard rock strata should be studied. The planning/design/techniques of shafts (chambers) in deep, high-temperature hard rock strata should be explored, and scientific characterization methods, index systems, and decision-making risk analysis models should be established. The high-temperature and high-pressure-resistant shaft lining structure design methods and hierarchical suspension subsidence techniques in deep, high-temperature hard rock strata as well as modification techniques and techniques for deep unstable rock strata should be developed.

Excavation technology and equipment for shafts (chambers) in deep high-temperature hard rock should be studied. The mechanical mechanism, rock-breaking method, cooling and slag discharge technology for excavation in deep high-temperature hard rock should be explored, and mechanical rock-breaking equipment systems, such as the drilling method, shaft boring machines, roadway boring machines, and the construction technology and process equipment system of integrated excavation/support, should be studied. The effects of high-temperature and high-pressure conditions on the wear of the drilling fluid medium and the teeth of drill bits/cutters should be analyzed to provide the technical requirements for solid lubricated hobs and to indicate new supporting materials suitable for high-temperature working conditions. A series of technologies for surrounding rock supports (e.g., theory, technology, and materials) in deep high-temperature hard rocks under long-term high-temperature and high-pressure conditions should be studied.

4.3.3 The key theories and technologies of coconstruction–coexistence–co-use of deep mining systems and geothermal development systems

Accurately surveying the occurrence characteristics, occurrence status, occurrence amount, and location of deep minerals and geothermal resources in mining areas, including the detailed distribution of the coexistence of minerals and geothermal resources is necessary. In addition, the engineering geological and hydrogeological conditions and the physical and mechanical properties of rock masses in deep mining areas should be explored to guarantee the optimal design of co-mining systems and safe, efficient, and precise mining.

According to the spatial distribution of the coexistence of minerals and geothermal resources, combined with the progress of deep geothermal energy exchange and transport technology, this study creatively proposes a method for the coconstruction and co-use of the mining structure of mineral resources and the geothermal development structure so that the mining system can provide the necessary main channel for geothermal development, while geothermal mining can provide an effective energy-saving means for cooling the mining operation.

Accurately surveying the engineering geological and high geostress environmental conditions of deep rock strata and rock mass structures in mining areas is necessary. The high ground stress during the construction of the co-mining system and the co-mining operation can lead to the strong deformation and failure of co-mining systems, the surrounding rock mass and the corresponding ground pressure activity, so the relevant process mechanism should be elucidated. Research to identify, predict, and control damage and risks should be conducted, and development mechanisms and strategies that consider the safety of mining systems and co-mining operations and the coordinated operation of mining and geothermal development should be developed.

The co-mining technology and remote-controlled intelligent operation method and technical equipment that adapt to deep high-temperature rock strata environmental conditions should be studied to improve the deep mineral and geothermal co-mining systems.

4.3.4 Theories and technologies of geothermal energy exchange and transport in deep high-temperature rock strata

Research on the physical and mechanical properties of high-temperature and high-pressure rock masses and the multiphysical field coupling theory should be conducted. Based on the evolution of rock mass damage, the mechanical properties, heat conduction characteristics, seepage, damage, fracture mechanisms and crack propagation patterns of rocks under high-temperature and high-pressure environments should be studied, and a numerical analysis of multiphysical field coupling should be conducted.

Research on the heat exchange mechanism and heat energy extraction technology of high-temperature and high-pressure rock masses should be conducted. Combining theoretical methods and experimental methods, with heat transfer in fractures as the leading factor, the heat transfer mechanism of the working medium-rock mass in the cracking zone and the heat energy extraction efficiency under different fracture networks and different heat exchange working mediums should be studied, and further analysis and optimization of heat transfer channels in high-temperature rock masses should be performed. The heat exchange mechanism of the cold-hot working medium and the convective heat transfer efficiency of different working mediums and different pipe layouts in underground artificial thermal storage areas also need to be analyzed.

Research on the theory and technology of high-temperature and high-pressure thermal energy transfer should be conducted. Theoretical derivation and numerical simulations should be combined to study the thermal energy transport mechanism of fracture flow and pipeline flow under high temperatures and high pressures and the supporting technology. The main object is the heat transfer

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process of the closed loop system (U-tube) under the complex conditions of high temperatures and high pressures and multiphase flow, and heat transfer and the transport processes should be analyzed using numerical simulations to optimize the heat transfer efficiency of the system.

Research and development of multitemperature-level thermal energy extraction systems should be conducted. Research and development of thermal energy extraction systems that can adapt to different rock mass temperatures, especially the cooling system in co-mining areas, should be conducted to provide an engineering basis for the technical scheme of "geothermal energy first and then mining". The multimedia heat exchange calculation program should be used to analyze the heat extraction efficiency and comprehensive production capacity of the system at each temperature level, which provides a basis for determining the capacity and service life of geothermal power generation systems in high-temperature rock strata.

5 Countermeasures and suggestions

5.1 Strengthening geological prospecting to provide information support for the co-mining strategy

Because of a lack of precedent for deep co-mining, the application and promotion of co-mining should start with a solid foundation, and geological exploration is the most basic starting point. A nationwide survey of deep mineral and geothermal resources are recommended to identify the distribution and types of resources, evaluate the reserves and exploitation potential of these resources, form a comprehensive technical support system for surveys, evaluate the scientific exploitation and utilization potential, and establish a solid foundation for the implementation of the co-mining strategy. Among the geothermal resources in deep high-temperature rock strata, the typical high-temperature geothermal resources that have the best prospect for future development and utilization but are currently not highly explored should be selected for exploration. For the four types of high-temperature geothermal resources, i.e., the radioactive heat generation type, the sedimentary basin type, the modern volcano type, and the intraplate active tectonic belt type, the resource reserves, the amount of exploitable resources, and the mining potential should be evaluated. For deep mines, fully investigating the occurrence of mineral and geothermal resources in the relevant area is necessary to determine the technical and economic feasibility of co-mining. The establishment of a public database or platform shared within the industry should be promoted to provide comprehensive information for the joint exploitation and utilization of minerals and geothermal resources and to maximize the utility of geological exploration data.

5.2 Promoting scientific and technological innovation to provide technical support for the co-mining strategy

Establishing major national science and technology projects and actively deploying relevant key projects are recommended. The major scientific and technological research plans for deep minerals and geothermal resources include basic research on the exploration and joint exploitation and utilization of deep minerals and geothermal resources, research on key technologies and equipment for the comprehensive development and construction of complex engineering projects in deep high-temperature and high-stress hard rock strata, and research on technology and equipment for the exchange, extraction and transport of geothermal energy from deep high-temperature rock strata. The research and development of special geothermal energy equipment and special technologies, especially for high-temperature rock drilling, artificial fracturing, cascade comprehensive utilization, tailwater recharge, anticorrosion and antiscaling, and underground heat recovery, should be strengthened. To cope with the trends of mineral resource development, the in-depth integration with big data, new mobile communication, the Internet of Things, high-performance computing and other technologies should be strengthened to improve resource and energy development. Gathering multidisciplinary professionals to focus on a series of difficulties and bottlenecks facing co-mining is recommended to achieve breakthroughs and to promote the collaborative innovation and development of key technologies, leading-edge technologies and modern engineering technologies for co-mining.

5.3 Formulating regulations and supportive policies to provide comprehensive support for the co-mining strategy

Technical standards for the exploitation and utilization of deep minerals and geothermal resources should be formulated as soon as possible, and relevant management measures should be promulgated in a timely manner to standardize and ensure activities, such as exploration, development, and utilization. The guidance and encouragement of the joint exploitation and utilization of deep minerals and geothermal resources should be strengthened, and incentive mechanisms, industrial policies, environmental protection regulations, and fiscal and taxation policies should be clarified. Fiscal and credit policies should be improved to encourage commercial banks to invest in the geothermal industry. The market regulation mechanism should be allowed to reasonably increase support for the units engaged in the joint exploitation and utilization of mineral and geothermal resources and related equipment and material manufacturing enterprises through tax reductions and exemptions. Unified national tax incentives for the joint exploitation and utilization should be introduced, and relevant renewable energy subsidy policies for geothermal heating and power generation should be implemented.

5.4 Incorporating into top-level national resource and energy planning and establishing scientific research demonstrations

The joint exploration, exploitation, and utilization of minerals and geothermal resources are a new way to promote China's energy transformation, achieve the carbon peak and carbon neutrality goals, and sustainably provide clean energy and green mineral products. The co-mining strategy should be incorporated into the national resource and energy development strategy for overall consideration, and the top-level design of the co-mining strategy should be established. A medium- and long-term parallel development route with both the clean development and utilization of fossil energy sources such as coal and green, low-carbon and clean new energy sources such as geothermal energy should be established to scientifically achieve a sustainable supply of mineral resources for the national economy and an increased proportion of new energy sources such as geothermal energy by replacing fossil energy sources.

It is recommended that four gold mines, namely, Sanshandao, Xincheng, Jinqingding, and Linglong, of the Jiaojia-style and Linglong-style gold deposits in the Jiaodong area, should be selected as test mining areas, and the demonstration and implementation should be organized as soon as possible. Scientific research demonstrations of co-mining should be established to promote implementation of the co-mining strategy and accelerate the formation of an integrated industry–university–research-based development pattern. Attention should be given to the brand effect during the exploitation and utilization of deep mineral and geothermal resources to contribute to the high-quality development of the mining and geothermal industries.

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