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CHARACTERISTICS AND GENESIS OF THE YANGBAJING GEOTHERMAL FIELD, TIBET

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ABSTRACT

The non-vocanic high-temperature Yangbajing Geothermal Field is located close to the convergent collision zone between the Indian and Eurasia plates. The Yangbajing convective system consists of shallow and deep reservoirs. The shallow reservoir is in unconsolidated Quaternary alluvium and altered Himalayan granite. Its temperature ranges from 150 to 165°C at depths between 180 and 280 m. The shallow sodium chloride thermal water is a mixture of deep thermal water and cold groundwater. The deep reservoir is in a slip-fault zone of the Nyainqentanglha core complex and fractured Himalayan granite. The deep reservoir can be subdivided into two parts: the upper part, with a temperature of 251°C, is between depths of 950 and 1350 m, while the lower part, below a depth of 1850 m, has temperatures as high as 329°C. No significant permeability has yet been encountered in the lower part. The deep thermal water is sodium chloride also, with a salinity of 2.8 g/l. Carbon dioxide is the major non-condensable gas in both reservoirs.

The Yangbajing Geothermal Field is in an active part of a large-scale slip-fault zone of a metamorphic core complex. Multiple tectonic activities caused tensional uplift and Proterozoic strata detachment and emplacement, which formed the core complex and a ductile shear-belt. It allowed an anatectic magma to rise and mix with the core complex to create a shallow magmatic heat source in the crust. Meteoric water is warmed as it flows down along tensional fractures and fissures of the core complex.

1. INTRODUCTION

The Yangbajing Geothermal Field is located 94 km northwest of Lhasa, the capital of the Tibet Autonomous Region, at elevations ranging from 4290 to 4450 m above sea level. It is a high-temperature geothermal field at the eastern end of the Mediterranean-Himalayan Geothermal Belt. The mean annual atmospheric pressure is about 600 mbar; the mean annual temperature is 2.5°C with extreme low temperatures of -30°C. The evapo-ration rate exceeds the annual precipitation. The field is in a southwest-northeast trending Cenozoic basin (Fig. 1). The basin is bordered by the Nyainqentanglha Range in the north and the Tang Range in the south. The Yangbajing Geothermal Field is just one of several hydrothermal areas present in the basin. The China-Nepal highway crosses the middle of the field dividing it into the southern and northern parts (Fig. 2). The shallow reservoir, composed of porous Quaternary alluvium, in the southern part is the discharge area of the field. There are two reservoirs in the upwelling northern part of the field. One is in shallow Quaternary alluvium and altered Himalayan granite. The other is the deep high-temperature reservoir in fractured Himalayan granite.

The first geothermal exploration began in 1976; it included geology, hydrology, geophysics, geochemistry, drilling, well testing, etc. A total of 45 exploration wells were completed and a hydrothermal area of 14 km^2 was delineated. Since the 1980s, an additional 25 production wells and 13 injection wells have been drilled. The first 1 MW$_e$ turbine ran successfully in September 1977. The installed capacity increased to 25.18 MW$_e$ in 1991 and the annual power generation had reached 10^8 kWh. So far, only the shallow reservoir has been exploited for power generation, a swimming pool and greenhouses. The pressure in the production wells has declined sharply due to limited recharge. There is now insufficient steam available to run the turbines at full load. The surface geothermal manifestations have disappeared except for a few fumaroles in the northern part of the field. Two deep exploration wells were drilled in the northern part of the field in 1993 and 1996 for new deep geothermal resources. This drilling discovered a high-enthalpy fluid. Well ZK4001 was drilled to a depth of 1450m in 1996. The two phase flowing wellhead conditions were 200°C and 1.5 MPa at a rate of 84 kg/s. This well is expected to support 12 MW of electricity (Dor Ji, et al., 1996). Well ZK4002 was completed at 2006.8 m depth in December 1993, but it has no stable flowrate due to low permeability.

More than 700 hydrothermal areas are known in the Tibetan Plateau. The hydrothermal areas are mostly distributed in two active tectonic zones. Prior to drilling the deep wells, most people believed thermal waters in Tibet were of meteoric origin with deep circulation in a region where the abnormally high geothermal gradient resulted from the decay of radioactive nuclides in rocks. This view has been changed by the exploration results for deep geothermal resources and geochemistry studies in the 1990s (Zhao et al., 2000). According to studies of tectonics, geophysics, geochemistry and petrology, the genesis of the Yangbajing Geothermal Field is suggested to relate to the slip-fault zone in the region. The heat source is now believed to result from partial melting of granite in a core complex. The core complex uplift is caused by tectonic movement of the Tibetan plateau. Colliding plates caused parts of the crust to remelt to magma (Dor Ji et al., 1997). The Yangbajing Geothermal Field is one of several non-volcanic high-temperature fields close to the convergent collision zone.

2. GEOLOGY BACKGROUND

2.1 Regional Tectonic Outline

Tibet is located on the southwestern Qinghai-Tibetan Plateau and at the eastern end of the famous Paleo-Tethys tectonic zone. The Qinghai-Tibetan Plateau consists of a series of terranes welded to each other by suture zones. Since the Cretaceous Period, relative movement between the Eurasian and Indian plates led to ocean closing and plates collision.

The Paleo-Tethys and Indian plate subsequently dove rapidly beneath a margin of the Eurasia plate. Persistent compression and isostatic equilibrium resulted in crustal thickening and rapid uplift to finally form the largest and one of the youngest plateaus in the world. The Tibetan Plateau contains volcanic arcs, three large-scale tectonic zones, faults, folds, hydrothermal mineral deposits, and recent geothermal active zones on the subducting plate. From a tectonics viewpoint, the Tibetan Plateau is composed of four terranes and three E-W striking suture zones. From north to south, they are as follows: the South Kunlun-Bayan Har Terrance, the Tuotuohe-Jinshajiang Suture Zone, the Qiangtang-Sanjiang Terrance, the Banggong-Nujiang Suture Zone, the Gangdise-Nyainqentanglha Terrance, the Yarlu-Zangbo Suture Zone and the Himalayan Terrance.

The northward moving India plate collided with the Eurasia plate and then dove to the lower part of the Eurasia plate margin. This resulted in the ocean crust uplifting and becoming a plate. The lower part of the Eurasia plate melted during the collision and then flowed up to emplace at shallow depths along the tectonic zone to provide heat for various hydrothermal systems in Tibet.

2.2 Geology of the Yangbajing Basin

The Yangbajing Basin is the largest among many active NE-SW striking tectonic zones in Tibet. It is bordered by the Yarlu-Zangbo Suture in the south and the Nyainquentanglha Range in the northwest. Faults developed at different stages; they arrange in steps and incline from the basin border toward the center. Fault scarps and terminal facets developed along fault lines and cluster directionally. Displacement of graben subsidence is in the range of 200 to 300 m. Tectonic activity is intense in the basin. The Quaternary till sheet step is sheared by NE striking faults and recent alluvium has been telescoped since the end of the Cenozoic Era. There were 30 earthquakes of magnitude 4.75 or greater between 1921 and 1991, demonstrating ongoing tectonic activity in the Yangbajing Geothermal Field.

The basin basement is an anticline of the Nyainquentanglha (Fig. 1). The axis consists of a Pre-Sinian complex. The two limbs are mainly Carboniferous and Cretaceous strata. There are magmatic intrusions but no Sinian to Devonian strata between the axis and limbs. It reflects characteristics of slip faulting superimposed on extension and uplift. The extension and uplift resulted from uplifting of the mantle, crust activation, and detachment of continent crust after the collision between the Gangdise-Nyainqentanglha Terrance and Himalayan Terrance. The Yangbajing graben (basin) and hydrothermal activity on the southern limb of the anticline developed on such tectonic condition of slip faulting.

The Yangbajing Geothermal Field is adjacent to the Gangdise volcanic arc in the south and the Nyainquentanglha Range core complex in the north. The high-temperature center of the field is situated in the hanging wall of the slip-fault zone where thermal fluid upwelling occurs. The southern part of the geothermal field is covered by widespread Quaternary alluvium, while the basement is Himalayan granite and tuff. The northern part of the field is underlain by Quaternary alluvium and altered Himalayan granite over dense granite and the Nyainquentanglha core complex. Shallow strata are intensively altered and often replaced by kaolinite. Northeast-southwest and northwest-southeast striking tensional faults have created a rhombohedral structural fabric (Fig. 2).

3. RESERVOIR FEATURES

Both the shallow and deep reservoirs belong to the same hydrothermal system. They are distinguished by different depths, temperatures, and salinities. The deep thermal water rises along faults in fractured granite. Near the surface, part of the fluid migrates laterally and mixes with cold groundwater before entering the shallow reservoir.

3.1 Shallow Reservoir

The shallow reservoir has an area of 14.8 km^2 and is hosted by porous Quaternary alluvium in most parts of the field except for a small area in the northern part composed of altered Himalayan granite. The temperature of the shallow reservoir decreases toward the southeast (Fig. 4). The shallow thermal water rises vertically near wells ZK354, ZK356 and ZK301 and then flows laterally toward the southeast. The shallow reservoir is generally between depths of 180~280 m corresponding to an elevation of 3800-4020 m above sea level.

The shallow reservoir is located beneath variable thicknesses of pelitic conglomerate or silty clay in Quaternary conglomerates, glacial sandy-gravel and weathered granite. The basement is Himalayan granite and tuff. Mylonitized granite is locally present in the northern part of the field. The temperature of the shallow reservoir is in the range 150~160°C. The sodium chlorite thermal water has a salinity of 1.5 g/l and a pH in the range of 7 to 9. The shallow thermal water is a mixture of the deep thermal water and cold groundwater. The Yangbajing geothermal power plant utilizes 1200 tons/day of the shallow thermal water. Production wellhead conditions are normally 125~140°C and 0.18~0.38 MPa. During the past two years, the pressure in the reservoir and in the production wells declined rapidly so that the turbines could not work at full load.

3.2 Deep High Temperature Reservoir

Geological, geophysical and geochemical surveys and logging data indicate the presence of deep geothermal resources in the northern part of the Yangbajing Geothermal Field. The deep reservoir is expected to have an area of 3.8 km^2 below a depth of 750 m. It is a typical bedrock-fractured geothermal reservoir. The location of the deep reservoir and migration of the deep thermal water are strictly controlled by the faults in the region. The thermal water is stored in fracture zones and tectonic fissures in rocks. The deep reservoir is found within mylonitized granite, granitic mylonite, and fractured granite that have characteristics of both ductile and brittle shearing. Alteration minerals include kaolinite, chlorite, calcite, quartz, pyrite, illite, sericite, analcitite, muscovite and biotite (Dor Ji et al., 1996). Mineral assemblages of chlorite, muscovite, and sericite appear vein-shaped at depths of 1000~1600 m, and are a product of hydrothermal activity at a temperature of about 300°C, close to that measured in well ZK4002.

The deep reservoir is covered by intensely altered and impermeable granite, haplophyre, and biotite-granite. Feldspars in the granite at shallow depths are replaced by kaolinite to make a more impermeable caprock. Wells

ZK4001 and ZK4002 show that the deep high-temperature reservoir consists of at least two parts. The upper part with a temperature 250~275°C is at depths ranging from 950 to 1350 m. The lower part has a temperature greater than 300°C and is below a depth of 1850 m but no production zone has been penetrated to date. The upper part is thicker than 350 m, with an average temperature of 248°C (Fig. 3). During production tests of well ZK4001 in 1996, the flowrate stabilized after only 20 minutes. Temperature and pressure increased slightly during a 15-day flow test. Wellhead conditions were 200°C and 1.5 MPa with two-phase fluid at 84 kg/s. The well is expected to produce 12 MW of electricity. The maximum temperature of 255°C was recorded at 1125 m depth in the well in 1997. The static fluid level in well ZK4001 is at 72 m depth and at 85 m depth in well ZK4002. The static level in well ZK4002 declined 6 m during the 15-day flow test of well ZK4001. It demonstrated that both wells are in the same hydraulic system and the wells are connected to each other. The deep thermal water is also a sodium chlorite fluid with a pH of 8.66 and a salinity of 2.8 g/l. Carbon dioxide is the main component of gases in the fluid, usually higher than 90% by volume. Other gas species are N_2, H_2S, H_2, CH_4, etc. The deep and shallow thermal waters have the same B/Cl ratio but have different Na/K ratios (Zhao et al., 2000).

4. GENESIS

Conceptual models of the Yangbajing Geothermal Field have been debated based on geology, tectonics, heat source, reservoir characteristics, thermal water migration and ascendant channels. There is no longer any argument that the Yangbajing Geothermal System is a typical convective system with a magmatic heat source.

4.1 Heat Source

The Yangbajing Geothermal Field is situated the intersection of the Nyainquentanglha core complex and the Gangdise volcanic arc. Magmatic activity has been quite extensive since the Late Cretaceous Period. Isotope dating shows the magmatic activity began in the Cretaceous Period. The Indian plate moved toward the north leading to the Tethys diving to the Eurasia plate. The process produced a huge anatectic magma and high background heat flow, resulting in melting of the lower crust. The anatectic magma then entered the upper crust under compressive stress.

During the Late Cretaceous to the Eocene, the Gangdise magmatic activities of intermediate-acid compositions formed a large-scale batholith, i.e. the Gangdise intrusive belt. The belt developed high-temperature contact metamorphism and intensive magmatization. Both imply the temperature of the magma was very high at that time. High contents of iron, magnesium and calcium in the granitic rocks indicate the magma originated in the lower crust.

From the Eocene to the Miocene, the two plates collided continually and magmatic activities began gradually to diminish. Magma changed from intermediate to silicic. The large-scale activity declined to scattered and isolated activity producing many small-scale batholiths. These batholiths have low contents of iron, magnesium and calcium. Low temperature contact metamorphism and weak migmatization can be observed surrounding the batholiths. These batholiths are of shallow isolated magma origin. Granite of 7~10 Ma age has been found in cores from wells ZK4001 and ZK4002, and in the south foothills of the Nyainquentanglha Mts. The core of the Nyainquentanglha core complex has bedded dikes that decrease in abundance from the core to rocks outside the core. The core complex is related to magmatic activity in the region.

There is a low velocity layer at 22 km depth in the Yangbajing area, inferred to be a magma body. Magnetotelluric prospecting performed by domestic and foreign geophysicists has revealed a low resistivity layer at 5 km depth, which is interpreted to represent a cooling magma.

The measured temperature in well ZK4002 is higher than 300°C below 1850 m depth. The thermal gradient exceeds 150°C/km in the well. If the melting point of granite is in the range 600 to 700°C, it appears that the magma should be present at a depth of 4 to 5 km in the Yangbajing Geothermal Field.

Mineralogy studies show biotite, muscovite, and sericite filling fissures in the cores of wells ZK4001 and ZK4002 at depths of 1270 to 1850 m. These mineral assemblages indicate temperatures exceeding 300°C. Many of these minerals are products of potassium-rich high-temperature hydrothermal fluid. The hydrothermal mineralogy suggests there is a high-temperature magma body underneath the Yangbajing Geothermal Field.

4.2 Tectonic Fracturing

The upwelling area in the Yangbajing Geothermal Field is situated along a N 35° E striking slip-fault zone at the south side of the Nyainquentanglha core complex. The slip-fault zone develops in Pre-Sinian metamorphic strata and stretches 150 km along the south side of the Nyainquentanglha Range. Geomorphic features are typically terminal facet and fault cliff. There are many hydrothermal areas along the fault; the Yangbajing Geothermal Field is just one of them. A fracture zone developed in the northern field is as wide as 1 km. The fracture zone is characterized by tectonic breccia, cataclastic rock, migmatite, a silicified zone, and hydrothermal alternation so that it is a typical of a large-scale slip-fault zone. The shallow part of the horizontal extension is defined by imbricate normal faults and cataclastic deformation. The deep expression of vertical compression is super-fractured mylonite and gneiss in which schistosity texture develops. The slip-fault zone appeared after the collision between the Himalayan and Gangdise-Nyainquentanglha Terranes and developed during conditions of uplift and extension.

The Yangbajing geothermal field is situated at an inflection point of the Nyainquentanglha slip-fault zone where it changes from a strike of N 60° E to N 30° E. This change represents a concentrated stress point in the region and caused NW striking faults to cut across NE striking faults. It also led to more pervasive rock fracturing and created a rhombohedral structural fabric (Fig. 2) as well as providing a channel for the magma to ascend.

4.3 Recharge, Runoff and Discharge

Recharge

Hydrogen and oxygen isotopic composition of hot and cold waters suggest the thermal waters are of local meteoric origin. Recharge areas are at elevations ranging from 4400 to 5800 m above sea level (Fig. 4). The main peak of the Nyainquentanglha Range is higher than 6000 m above sea level. Snow continuously covers the peak and recently a glacier has developed in the range. The glacier is a large solid reservoir for the geothermal fluid. The thermal water originates from meteoric water (snow, ice, rain, etc.) heated by the magma chamber.

Runoff and discharge

Assemblage, storage, and migration of the thermal waters are through faults and fractures. Primitive joints within the core complex, subsidiary fractures, and brittle detachment space within the fault zone are filled with meteoric water. The dense cold groundwater pulled by gravity moves down through the fracture zone. Along the flow path, the water absorbs heat from wallrock and gradually loses its density. Differential densities between the thermal and cold waters drive the thermal water to shallow depths. It is then stored in a closed system to form high-temperature reservoir. Deep NW, SN and even EW striking faults provide channels for the ascending thermal waters in addition to the slip-fault zone in the region. When the thermal water approaches the surface, the pressure in the fracture zone decreases so that the thermal water can boil. CO_2- and H_2S-rich steam escaping from the boiling water alter the wallrock along its ascent channel. When steam cools, it condenses to acidic water. When the upflow of the deep thermal water is blocked, the pressure drives it laterally toward the southeast where it enters the shallow reservoir after mixing with the cold groundwater. The shallow reservoir consists of Quaternary alluvium and altered granite.

5. CONCLUSIONS

The high-temperature Yangbajing Geothermal Field consists of both shallow and deep reservoirs. The shallow reservoir is primarily located in porous and unconsolidated Quaternary alluvium. The deep reservoir is in fractured Himalayan granite. Temperatures range 250 to 275°C in the upper part of the deep reservoir and exceed 300°C at greater depths. Faults control the thermal water migration in the field. The regionally active slip-fault zone controls the shallow upwelling area. The formation of the slip-fault zone is related to tectonic movement of terranes in Tibet. It was a right lateral strike-slip fault before the Jurassic and changed to a left strike-slip fault after the Jurassic. Proterozoic Erathem (Anznn) detachment and emplacement caused the core complex and ductile shear-zone. Part of the anatectic magma invaded the core complex and formed a shallow crustal magma chamber at 4~5 km depth providing the heat source for the geothermal system. Since the late Pleistocene, the Nyainquentanglha Range uplifted rapidly. The middle Pleistocene and Holocene sediments are deposited in the Yangbajing basin.

Fractures on the border of the basin were activated again and tectonic movement developed NE and NW striking subsidiary fractures in the basin creating a series of rhombohedral blocks. Meteoric water along the slip-fault zone of the core complex, particularly in shallow tensional fractures and primitive joints, moves down and is heated by the magma chamber to form a hydrothermal convective system. High temperature geothermal fluid flows from the center of the fault-zone and then ascends to the near surface along faults.

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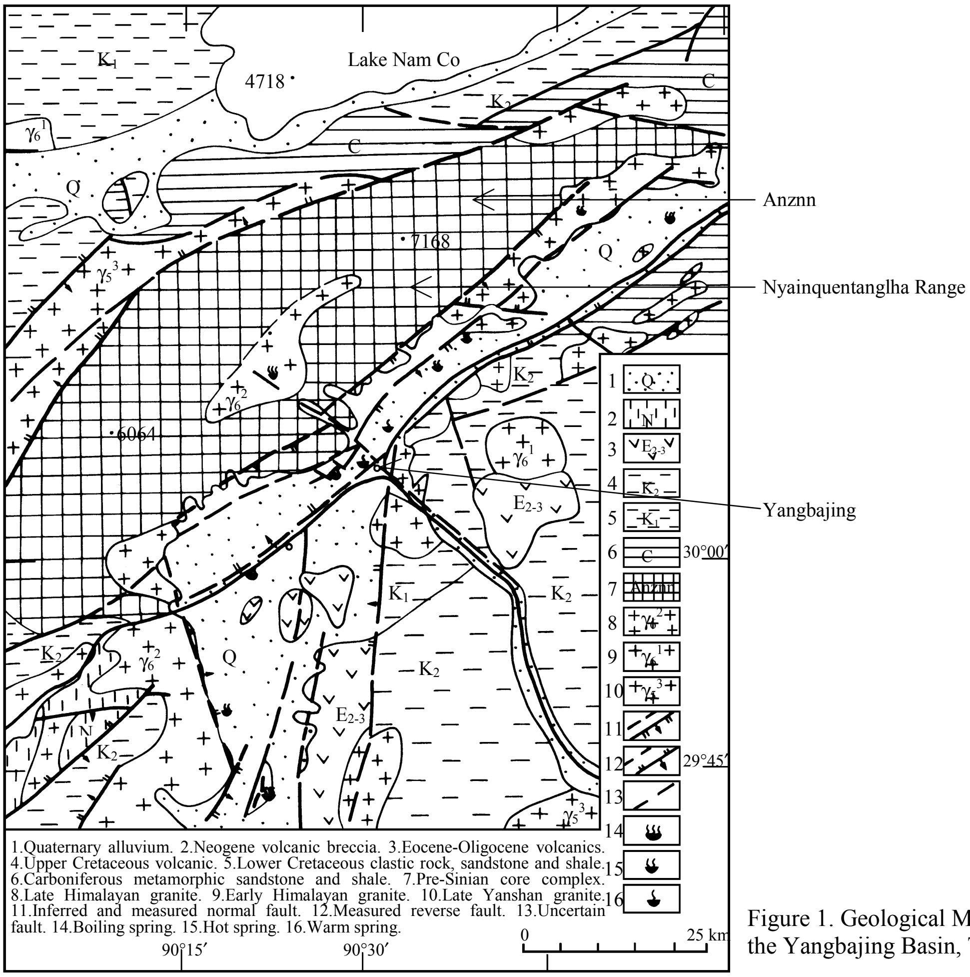


1.Quaternary alluvium. 2.Neogene volcanic breccia. 3.Eocene-Oligocene volcanics. 4.Upper Cretaceous volcanic. 5.Lower Cretaceous clastic rock, sandstone and shale. 6.Carboniferous metamorphic sandstone and shale. 7.Pre-Sinian core complex. 8.Late Himalayan granite. 9.Early Himalayan granite. 10.Late Yanshan granite. 11.Inferred and measured normal fault. 12.Measured reverse fault. 13.Uncertain fault. 14.Boiling spring. 15.Hot spring. 16.Warm spring.

Figure 1. Geological Map of the Yangbajing Basin, Tibet

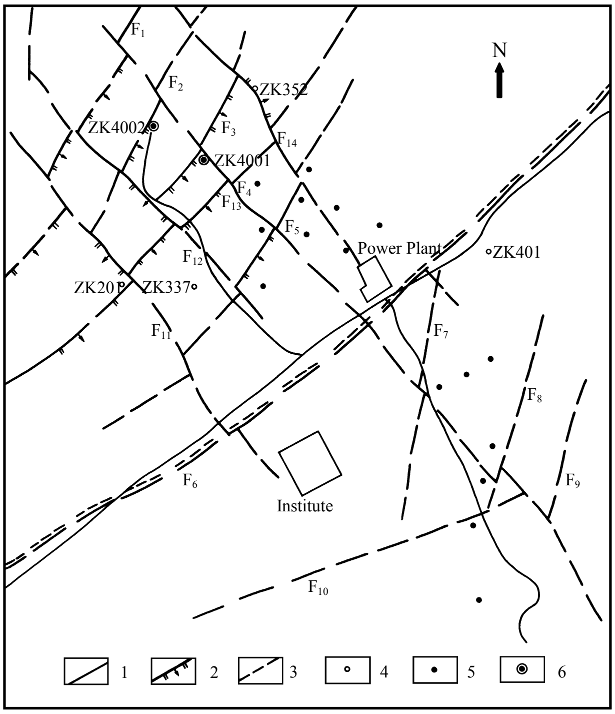


Figure 2. Sketch Map Showing Geological Structures in the Yangbajing Geothermal Field

1. Road. 2. Observed fault.
3. Buried or inferred fault.
4. Exploration well.
5. Production well.
6. Deep well.

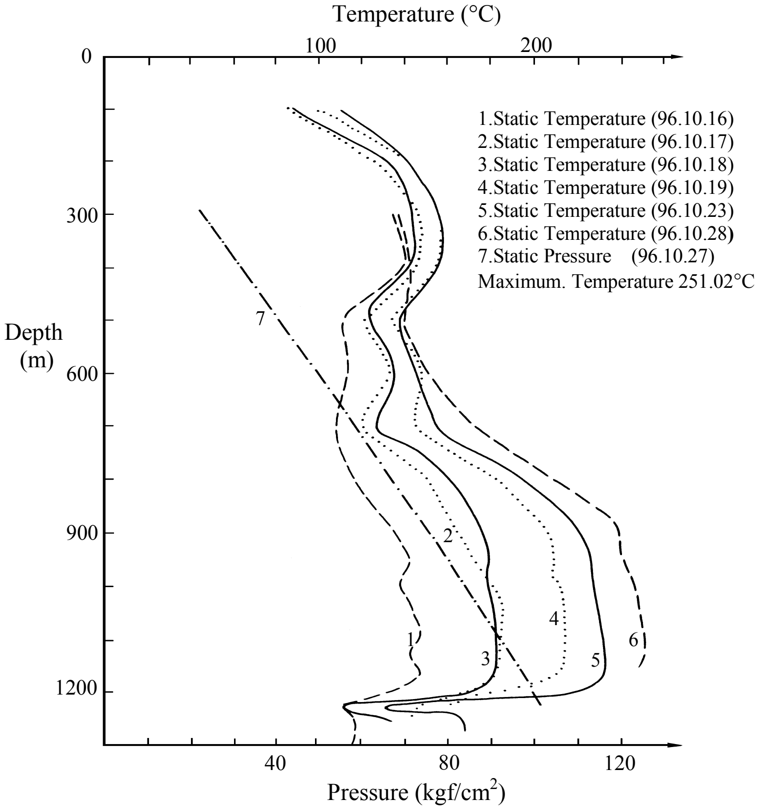
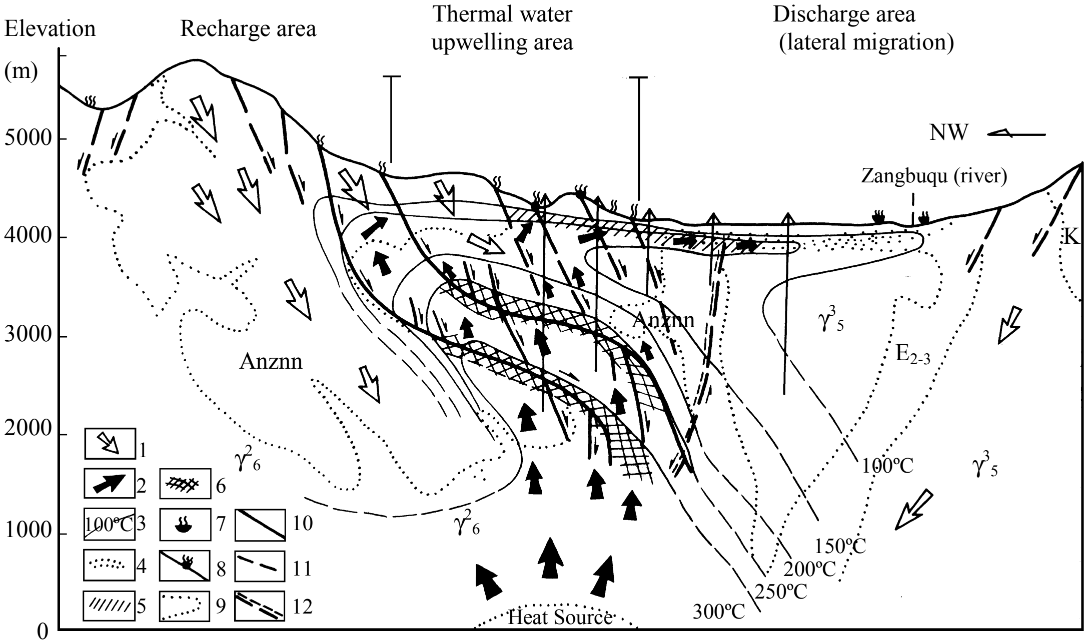


Figure 3. Temperature and Pressure Logs from Well ZK4001



1. Meteoric water. 2. Upwelling thermal water. 3. Isothermal line. 4. Quaternary porous reservoir. 5. Shallow reservoir of fractured granite. 6. Deep reservoir of fractured granite. 7. Hot spring. 8. Steaming ground. 9. Geological boundary. 10. Sliding plane. 11. Normal fault. 12. Buried fault.

Figure 4. Conceptual Model of the Yangbajing Geothermal Field, Tibet