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INVESTIGATION OF HEAT EXTRACTION FROM SUPERCRITICAL GEOTHERMAL RESERVOIRS

Toshiyuki Hashida[1], Kazuo Hayashi[2], Hiroaki Niitsuma[3], Koji Matsuki[3],
Noriyoshi Tsuchiya[3] and Katsuto Nakatsuka[3]
[1] Fracture Research Institute, Tohoku University, 01 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan
[2] Institute for Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577 Japan
[3] Department of Geoscience and Technology, Tohoku University, 01 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

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ABSTRACT

This paper presents the outlines of a new project on "Investigation on Design Methodology of Supercritical Subsurface Boiler for Next Generation Geothermal Energy Extraction (1997-2002)" at Tohoku University. The "Supercritical Subsurface Boiler" refers to an underground heat exchanging system which takes advantage of the thermal energy transferred to supercritical water. The goal of the project is to establish the potential of supercritical water as heat extraction fluid, and to develop a design methodology for supercritical geothermal reservoirs with the objective of enhancing the geothermal energy output. The selected research tasks are concerned with (1) fracture mechanics study of the formation processes of supercritical reservoirs, (2) dynamics of supercritical reservoirs (supercritical water-rock interactions), (3) subsurface structure and stress monitoring method, and (4) thermal evaluation. Brief descriptions of the research tasks set up for the project are presented, together with recent preliminary results from the individual research tasks.

1. INTRODUCTION

The HDR/HWR experiments conducted to date as well as current commercial geothermal power plants have reservoir temperatures that are below the critical temperature of water. This limited use of the renewable resource has prompted a trend toward research and development for the extraction of thermal energy from hotter and deeper rock masses. Many attempts are being made to understand and utilize the natural hydrothermal system under supercritical water conditions (e.g. Hanano, 1998; Schroeder, 1998).

It has been demonstrated through a NEDO research project "Deep-Seated Geothermal Resources Survey" that in the Kakkonda geothermal area, located in northeast Japan, the rock temperature reaches 500°C at approximately 3.5 km depth (Ikeuchi et al., 1996). The temperature data of an exploration well, WD-1a drilled at Kakkonda is reproduced in Fig. 1, together with that for well 18 which is close to the WD-1a well. It is particularly noted that the temperature and pressure conditions below about 3.1 km exceed those at the critical point of water (374 °C, 22 MPa). The supercritical water region is labelled in Fig. 1 (assuming pure water at hydrostatic pressure). This observation suggests that the fluid associated with thermal extraction from the hotter rock mass may be supercritical, although the effect of various chemical species present in geothermal fluid needs to be studied. Although the >500 °C at the bottom of well WD-1a is the highest temperature measured in a geothermal well in the world, the thermodynamic conditions in excess of 374 °C and 22 MPa are not unique. In fact, high temperature rock masses under supercritical water conditions have been also found in the Tuscany geothermal areas and the Phlegrean fields in Italy (Capetti et al., 1985 and Barberi et al., 1984), and in the Nesjavellir geothermal field in Iceland (Steingrimsson et al., 1990). The surveys also suggest the presence of "supercritical rock mass" just few kilometers underneath the existing geothermal reservoir. Thus production from deep geothermal reservoirs although challenging will provide increased energy extraction from temperatures greater than 350°C (see Fig 2).

In order to address the potential of creating supercritical geothermal reservoir, a new project "Investigation on Design Methodology of Supercritical Subsurface Boiler for Next Generation Geothermal Energy Extraction (1997-2001)" has been launched at Tohoku University. This five year research project is being supported by the Japan Society for the Promotion of Science (JSPS). The "Supercritical Subsurface Boiler" refers to an underground heat exchanging system which takes advantage of the thermal energy transferred to supercritical water. The outlines of the research project and research tasks are described in this paper.

2. RESEARCH TASKS AND PRELIMINARY RESULTS

The following investigations form the major research tasks of the project:

(1) Task A: Evaluation of fracture criteria of rock masses and formation process of supercritical reservoirs
(2) Task B: Dynamics of supercritical reservoirs: chemical interaction between supercritical water and rock
(3) Task C: Development of methods for monitoring supercritical reservoirs and for determining tectonic stresses
(4) Task D: Development of a predictive model for the performance of thermal extraction from supercritical reservoirs

The tasks A and B include laboratory study and field surveys to characterize the fracture system in intact supercritical rock masses. These may control the formation process of supercritical reservoirs. The research of tasks A-C are designed to support the thermal evaluation (task D). In the following section, a brief description of the individual research tasks is presented, along with some preliminary results obtained to date.

2.1 Formation Process of Supercritical Reservoirs (Task A)

It is an important first step to determine the fracture characteristics of rocks in a supercritical water environment for the prediction of the fracture process during hydraulic injection. To this end, a triaxial apparatus was installed to conduct tension and compression tests under confining pressures and to determine the deformation and fracture properties of rocks in the presence of supercritical water. Rock samples ranging in diameter from 20 mm to 35 mm can be tested under servo-controlled loading and pore pressure conditions. Triaxial tests conducted on several types of granite have shown that fractures can be characterized by the formation of macroscopic brittle cracks both in tension and compression in a supercritical water environment up to 500 °C and 150 MPa (confining pressure). As far as the fracture characteristic of the rocks is concerned, the occurrence of brittle fracture may suggest the feasibility of creating artificial cracks in supercritical rock mass by hydraulic injection. Fig 3 shows the peak shear strength as a function of pore pressure obtained for Iidate granite and Westerly granite at 500 °C and confining pressure of 150 MPa (Takahashi et al., 1999). It is seen that the presence of supercritical water reduces the shear strength by 25-30% over that in the dry condition. In addition, relationships between the cohesive crack stress and the opening/slip displacement for opening and shear crack growth are being measured by conducting triaxial tests in order to select suitable fracture criteria. The fracture criteria will be incorporated into a numerical simulation code to predict the fracture growth induced by hydraulic injections under a given tectonic stress state (Sato and Hashida, 2000). An embedded crack element method is employed for the numerical code in order to simulate the mixed mode growth of the hydraulically-induced fracture.

Laboratory-scale hydraulic injection tests are in progress to verify the numerical simulation code and to observe directly the formation process of supercritical reservoirs under simulated tectonic conditions. Fig 4 gives a schematic illustration of a triaxial apparatus developed for simulated hydraulic injection tests. Thick-walled cylindrical specimens of 45 mm outer diameter and 5 mm in inner diameter can be tested. The maximum temperature, borehole pressure (internal pressure), and confining pressure achievable with the triaxial apparatus are 600 °C, 300 MPa, and 150 MPa, respectively. Preliminary hydraulic injection tests have been conducted at 25, 300, and 600 °C under confining pressure of 100 MPa. The tests at 600 °C produced no macroscopic fracture at a flow rate of 5.0-50.0 mm^3/sec without appreciable pressure difference between the borehole pressure and the confining pressure, while vertical fractures along the borehole axis were formed as usual at 25 and 300 °C. The preliminary tests suggest the possibility of creating a porous-type reservoir in supercritical rock masses. More detailed and extensive tests are being carried out to look into the extremely enhanced flow behavior of supercritical water.

2.2 Dynamics of Supercritical Reservoirs (Task B)

It is well accepted that the formation of artificial geothermal reservoirs by hydraulic injection strongly depend on the natural fracture system in the rock mass. Indeed, the majority of the HDR/HWR experiments indicate that the jacking and/or shear dilation of pre-existing natural fractures is one of the mechanisms controlling the reservoir formation for naturally fractured rock. However, there is almost no knowledge of the nature of the rock mass where the temperature exceeds the critical temperature of water. As shown schematically in Fig. 5, geological field surveys using a natural analogue and laboratory experiments on supercritical water-rock interactions are being performed in order to provide fundamental information for the design and control of supercritical geothermal reservoirs. The Takidani granite in the Japan Alps, believed to be the youngest exposed granitic pluton on the Earth (Harayama, 1992), was selected as a natural analogue of supercritical rock masses. The geology and petrology of the Takidani pluton are described in Bando and Tsuchiya (2000). The cooling history of the Takidani granite deduced using various dating methods is shown in Fig. 6 (Tsuchiya and Fujino, 2000). The simple cooling history and the wide outcrop of the Takidani granite enables us to conduct a systematic investigation on the condition for the occurrence of natural fractures and the overall distribution of natural fractures within the pluton (Kano and Tsuchiya, 2000). Two types of the fluid inclusions were observed in quartz of the Takidani pluton, and secondary fluid inclusions were closely aligned with a macrocrack plane observed in the outcrop. Homogenization temperatures of the secondary fluid inclusions were in the range of 256-327 °C (Sekine and Tsuchiya, 2000). Those temperatures were corrected for real trapping temperatures using an emplacement pressure. The most relevant formation temperature of secondary fluid inclusions, which is a measure of the lower bound for the fracture formation, is considered to be approximately 400 °C. Detailed analyses using the fluid inclusion method is now underway to understand the nature of supercritical rock masses, especially in terms of accurate prediction of the emplacement pressure and effects of salinity of fluid inclusions to an isochore.

Investigation of supercritical fluid–rock interactions, including dissolution and precipitation in multi-component systems, is also in progress using batch and flow through autoclaves (Hirano et al., 2000). Dissolution experiment indicated that the solubility of Iidate granite at supercritical water conditions was significantly lower than that in the sub-critical region. The reduced water-rock chemical interaction suggests that the heat extraction from supercritical reservoirs may be useful to overcome the plugging of fluid flow paths due to precipitation and provide a more controllable route compared with sub-critical rock masses where higher dissolution and precipitation rates are expected.

2.3 Subsurface Structure and Tectonic Stress Monitoring (Task C)

Subsurface structure

AE reflection method (Soma and Niitsuma, 1998), and drill bit reflection method (Asanuma et al., 1998) are being further developed to monitor subsurface structures and detect artificial reservoirs at supercritical water conditions. The majority of the conventional surface seismic techniques may be inapplicable because only a very limited amount of seismic energy can penetrate into deep-seated rock masses from the surface due to significant attenuation. In contrast, the above-mentioned two methods, which have been recently developed in the course of MTC project (Niitsuma, 1995), may have a high potential for the measurement of deep-seated supercritical geothermal reservoirs. The AE reflection method takes advantage of naturally-occurring micro-seismic events as a source for reflection survey. The drill bit reflection method uses drilling-induced micro-seismic signals as an acoustic source. The principles of those reflection methods are schematically shown in Fig. 7. In the present project, we will further develop the AE reflection method and the drill bit reflection method in order to develop a new signal processing method for detecting reflected waves from reservoirs at the great depth, and to develop a monitoring method for delineating its spatial distribution. Fig 8 shows an example of results of the AE reflection method applied to Kakkonda geothermal field, Japan (Sato et al., submitted). The planes shown in Fig. 8 indicate reflectors with higher intensities detected by the AE reflection method. It is particularly noted that the AE reflection method detects the upper boundary of the Kakkonda granite whose temperature exceeds the critical temperature of water.

The triaxial apparatus described in the previous section is also designed to enable velocities of 1 MHz acoustic waves to be measured along the cylindrical sample axis at supercritical water conditions. The measurement of elastic wave velocity is used as a fundamental data base to support the development of the AE reflection method and the drill bit reflection method for monitoring supercritical geothermal reservoirs.

Tectonic Stress

Several methods are being studied to determine tectonic stresses in deep-seated rock masses: the drilling-induced tensile fracture method (Okabe et al., in press), natural fracture method (Itoh et al., 1999), and core-based methods (Matsuki, 1994; Matsuki et al., 1995).

It is known that at greater depths, borehole drilling is sometimes accompanied with the formation of a longitudinal crack consisting of many sub-parallel microcracks which are oblique to the borehole axis. The drilling-induced tensile fracture (DTF) method determines the three-dimensional tectonic stress field using the circumferential position of DTF along the borehole surface and the inclination of the microcracks with respect to the borehole axis, as illustrated in Fig. 9. In this study, the effect of the thermal stresses induced by drilling on the stress determination is being examined in order to apply the DTF method to deep-seated rock masses. Figs 10 (a) and (b) show an example of the predicted magnitude and orientation of the tectonic stresses under the given thermal stresses (Hayashi et al., 1998). In this example, it is shown the DTF method can determine the orientation of the tectonic stresses as well as their magnitude when the thermal stress induced by drilling is less than 10 MPa. A natural fracture method is under development, which gives a possible range of the stress magnitude and orientation on the basis of orientations of hydraulically conductive natural fractures. The core-based methods include anelastic strain recovery (ASR) method and the differential strain curve analysis (DSCA) method. Laboratory experiments using the triaxial apparatus described above are planned to examine the applicability of the core-based methods to deep-seated rock masses. A comprehensive tectonic stress evaluation method will be proposed for the characterization of the supercritical rock mass by combining the above-mentioned methods in the course of the project.

2.4 Thermal Extraction Evaluation (Task D)

Several numerical models have already been developed, which allow the mass and heat transfer in natural geothermal systems to be simulated taking into account the effects of the properties of supercritical water (e.g. Hanano, 1998;.White, 1998). Depending on the type of artificial reservoir expected for supercritical rock masses, numerical simulation code will be constructed for the thermal extraction analysis at the stage of water circulation. Thus far, numerical simulations have been conducted assuming a single fracture type reservoir as an initial reservoir model. The simple model was primarily used to examine the effect of the thermal and fluid flow properties of supercritical water, such as heat capacity, density and viscosity on the thermal extraction performance. Some results of the numerical simulations are reported elsewhere (Watanabe et al., 2000). The present numerical model will be further developed on the basis of the studies of the formation process of supercritical geothermal reservoirs. Experimental data regarding the flow behavior of supercritical water in rocks will be collected employing the hydraulic fracturing simulator and used as an input for the thermal extraction analysis. The primary objective of such numerical simulations is to establish the advantage of the use of supercritical water for the geothermal energy extraction.

3. CONCLUDING REMARKS

The primary objective of the research project described here is to look at the possibility of creating artificial reservoirs in deep-seated rock masses where the temperature exceeds the critical temperature of water. The use of supercritical water with its significantly higher heat capacity is expected to be useful for increased extraction of the heat energy stored in rock masses. In addition, the recent hydraulic injection experiment conducted on cylindrical rock specimens suggests that supercritical water may permeate pervasively in rock masses with no apparent pressure difference. This enhanced permeability of supercritical water may make it possible to create a porous type reservoir and to access heat in a larger rock volume than would be possible with a fractured type reservoir at 200-300 °C. Further detailed investigation is required to confirm the possibility of creating a porous type reservoir in supercritical rock mass.

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REFERENCES

Asanuma, H, Liu, H., Niitsuma, H. and Baria, R. (1998). Imaging of structures in basement rock by the drill bit reflection method, *Proc. 4th SEGJ Int. Sympo.* pp.369-374.

Bando, M. and Tsuchiya, N. (2000). Petrologic characterization of the Quaternary volcano-plutonic system: the Takidani pluton and associated volcanic rocks in the Japan Alps, Japan., *Proc. WGC 2000*, in this volume.

Barberi, F., Corrado, G., Innocenti, F. and Luongo, G. (1984), Phlegraean fields 1982-1984: Brief chronicle of a volcano emergency in a desnsely populated area, *Bull. Volcanol.*, Vol. 47-2, pp. 175-185.

Cappetti, G., Romano, C., Cigni, U., Squarci, P., Stefani, G. and Taffi, L. (1985), Development of deep exploration in the geothermal areas of Tuscany, Italy, *GRC, Int. Sympo. on Geothermal Energy*, Int., pp. 303-309.

Hanano, M. (1998), A simple model of a two-layered high-temeprature liquid-dominated geothermal reservoir as a part of a large-scale hydrothermal convection system, *Transport in Porous Media*, Vol. 33, Nos. 1-2, pp. 3-27.

Harayama, S. (1992). Youngest exposed granitoid pluton on the Earth: Cooling and rapid uplift of the Pliocene-Quaternary

Takidani Granodiorite in the Japan Alps, central Japan. *Geology*, Vol.20, pp.657-660.

Hayashi, K. Naehashi, A. and Okabe, T. (1998). Effects of thermal stress in the tectonic stress determination by drilling-induced tensile fracture method, *Proc. of 1998 Annual Meeting Geothermal Research Society of Japan*, p. I-6.

Hirano, N., Tsuchiya, N. and Nakatsuka, K. (2000). Water-Rock interaction of granites under subcritical and supercritical hydrothermal conditions. *Proc. WGC 2000*, in this volume.

Ikeuchi, K., Komatsu, R., Doi, N., Sakagawa, Y., Sasaki, M., Kamenosono, H and Uchida, T. (1996). Bottom of hydrothermal convection found by temperature measurements above 500 □C and fluid inclusion study of WD-1 in Kakkonda geothermal field, Japan, *Geothermal Resources Council Transactions*, Vol. 20, pp.609-616.

Kano, S. and Tsuchiya, N. (2000). Field observation of cooling joint system in the Quaternary Takidani pluton., *Proc. WGC 2000*, in this volume.

Matsuki, K. And Takeuchi, K. (1994). Three-dimensional in-situ stresses determined by ASR method at Yunomori geothermal field, Japan, *J. The Mining and Materials Processing Institute of Japan*, Vol. 110, pp. 625-630.

Matsuki, K., Shimizu, T., and Okumura, K. (1995). Evaluation of microcracks in rock by differential strain curve analysis, *J. The Mining and Materials Processing Institute of Japan*, Vol. 111, pp. 607-615.

Niituma, H. (1995). New international collaborative project on advanced microseismic mapping/imaging techniques for geothermal development, *Proc.WGC 1995*, pp.803-805.

Okabe, T., Hayashi, K., Shinohara, N. And Takasugi, S. (in press). Inversion of drilling-induced tensile fracture data obtained from a single inclined borehole, *Int. J. Rock Mech., Min. Sci. & Geomech. Abstr.*

Pine, R.J., and Batchlor, A.S. (1984). Downward migration of shearing in jointed rock during hydraulic injections, *Int. J. Rock Mech., Min. Sci. & Geomech. Abstr.*, Vol. 21, pp.249-263.

Sato, K. and Hashida, T. (2000). Numerical Simulation of Hydraulic Fracturing in Hot Dry Rock under Supercritical Water Condition - Effect of Tectonic Stress, *Proc. WGC 2000*, in this volume.

Sato, K, Soma, N., Niitsuma, H., Tateno, M. and Ohminato, T. (submitted). Mapping/imaging of the Kakkonda geothermal field, in Japan, by an acoustic reflection method and logging data analyses, *Proc. of AE Conference in Rreservoir Engineering and Civil Engineering*.

Schroeder, R., Takasugi, S. and Osato, K. (1998), On deep seated geothermal resources, *Proc. 23rd Workshop on Geothermal Reservoir Engineering*, Stanford University, CA, SGP-TR-158, 1998, pp.451-460.

Sekine, K. and Tsuchiya, N. (2000). Development of microcracks in granites clarified by fluid inclusion study: examples from the Quaternary Takidani pluton, *Proc. WGC 2000*, in this volume.

Soma, N. and Niitsuma, H. (1997). Identification of structures within the deep Geothermal reservoir of the Kakkonda field, Japan, by a reflection method using acoustic emission as a wave source, *Geothermics*, Vol. 26(1), pp.43-64.

Steingrimsson, B., Gudmundsson, A., Franzson, H., and Gunnlaugsson, E. (1990), Evidence of a supercritical fluid at depth in the Nesjavellir field, *Proc. 15th Workshop on Geothermal Reservoir Engineering*, Stanford University, CA, SGP-TR-130, pp. 81-88.

Takahashi, T., Tamaya, H. and Hashida, T. (submitted). Fracture process of granite under supercritical water environment, *Trans. JSME (A)*.

Tsuchiya, N. and Fujino, K. (2000). New thermoluminescence technique for evaluating cooling history and geothermal activity of the Quaternary Takidani pluton., *Proc. WGC 2000*, in this volume.

Watanabe, K., Niibori, Y., and Hashida, T. (2000). Numerical Study on Heat Extraction from Supercritical Geothermal Reservoirs, *Proc. WGC 2000*, in this volume.

White, S.P. and Mroczek, E.K. (1998), Permeability changes during the evolution of a geothermal field due to the dissolution and precipitation of quartz, *Transport in Porous Media*, Vol. 33, Nos. 1-2, pp. 81-101.

Willis-Richards, J. and Wallroth, T. (1995). Approaches to the modelling of HDR Reservoirs: A review, *Geothermics*, Vol. 24(3), pp. 307-332.

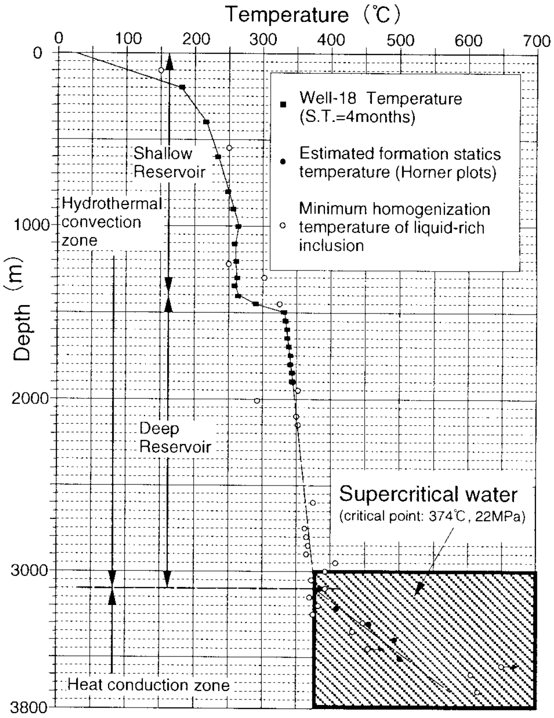


Fig. 1 Temperature profile of WD-1a and Well-18 at Kakkonda geothermal field, Japan.

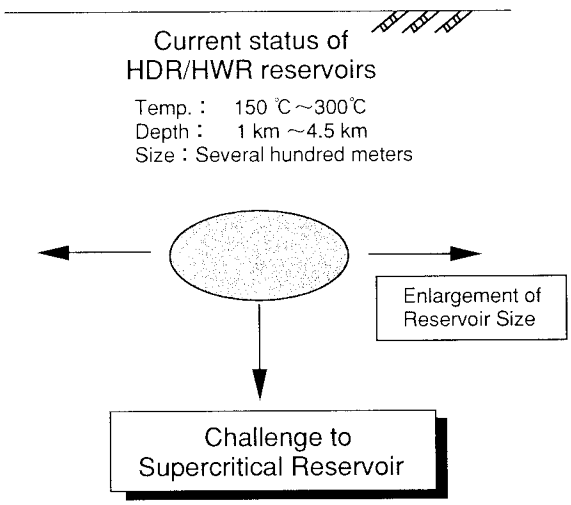


Fig. 2 Current status of HDR/HWR reservoirs and future research direction.

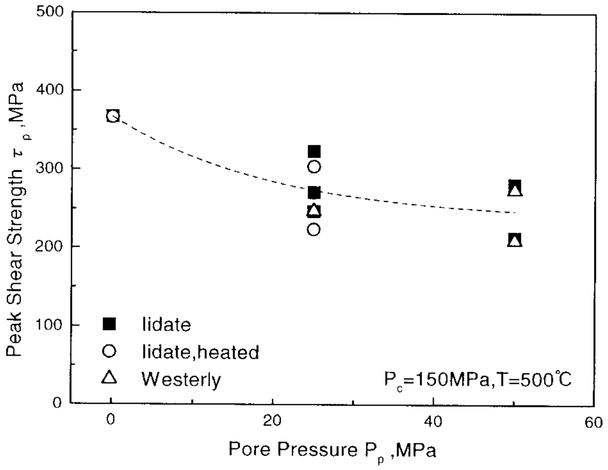


Fig. 3 Peak shear strength as a function of pore pressure.

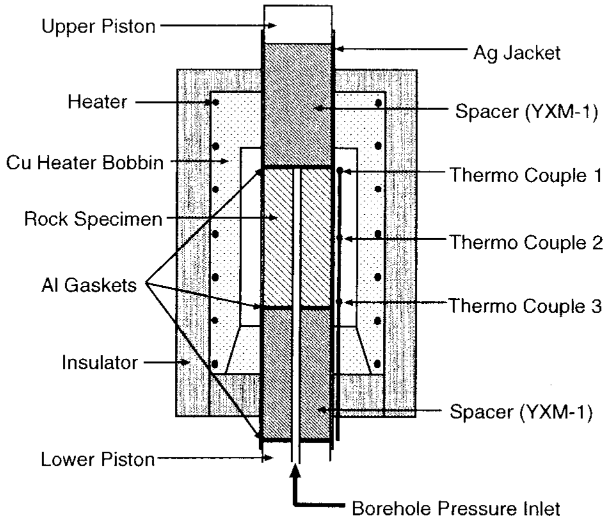


Fig. 4 Schematic of triaxial apparatus for hydraulic injection experiment.

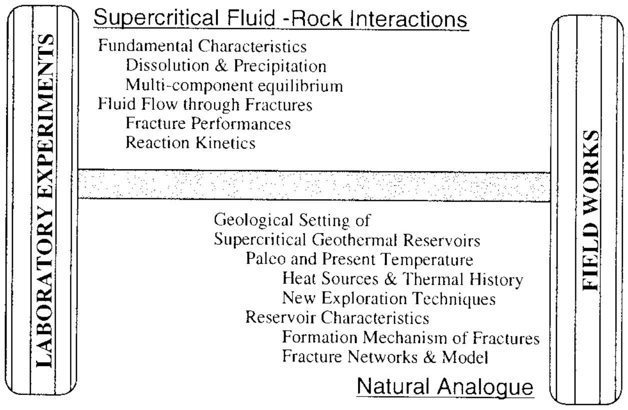


Fig. 5 Research subjects of task B.

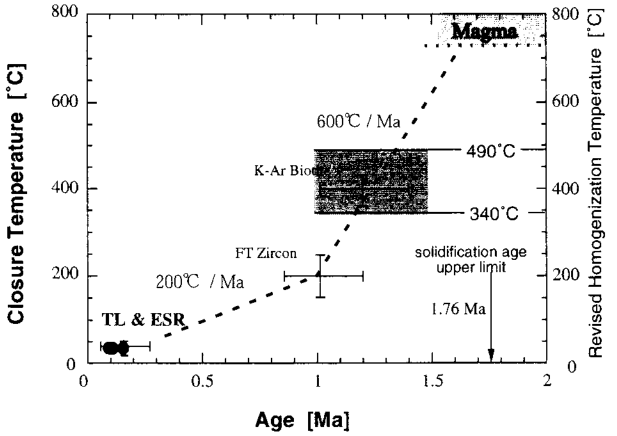


Fig. 6 Cooling history of the Takidani granodiorite in the Japan Alps.

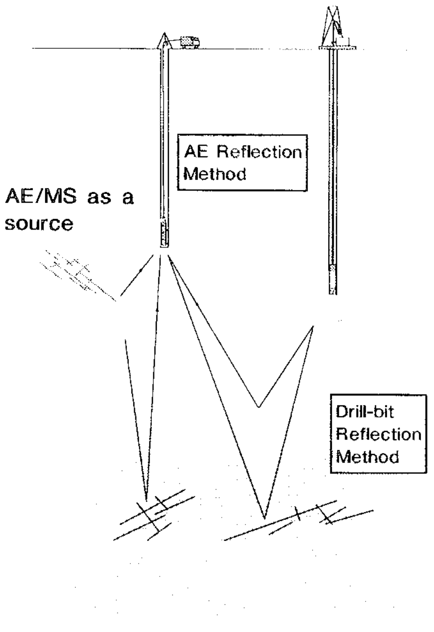


Fig. 7 Principle of AE reflection method and drill bit reflection method.

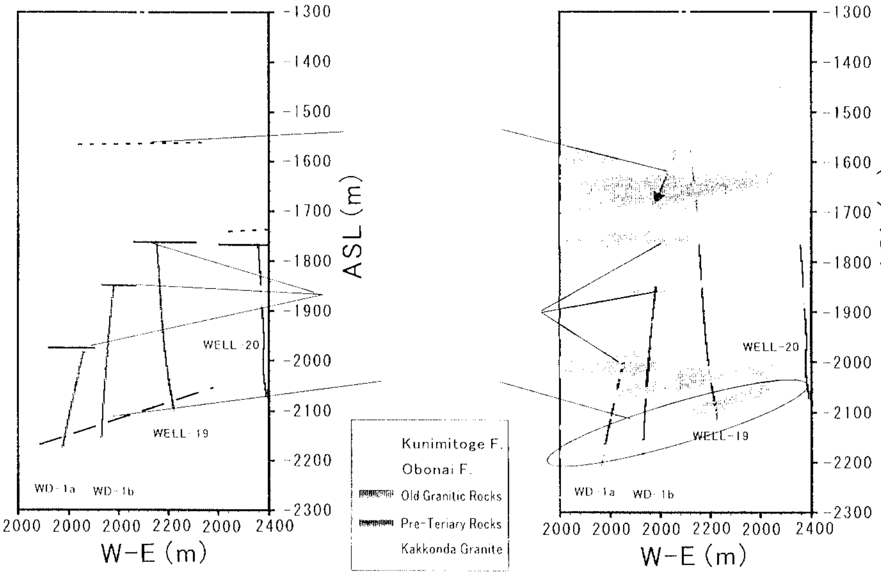


Fig. 8 Reflectors delineated by the AE reflection method and geological cross section of Kakkonda geothermal area.

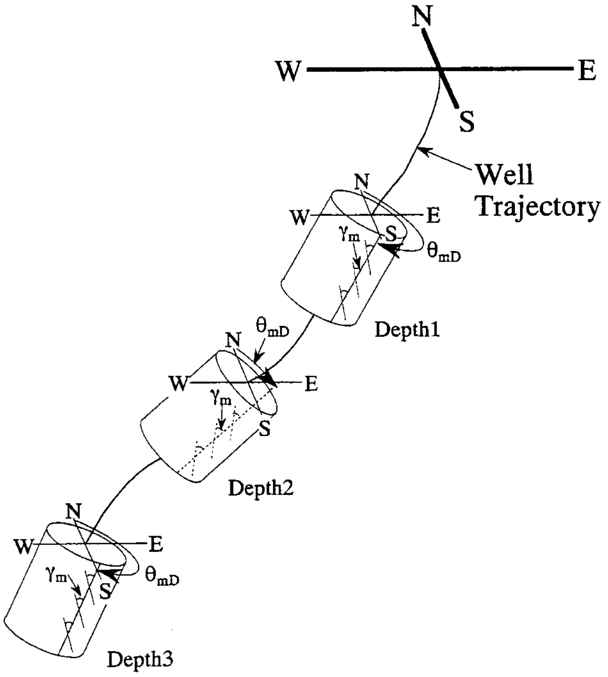
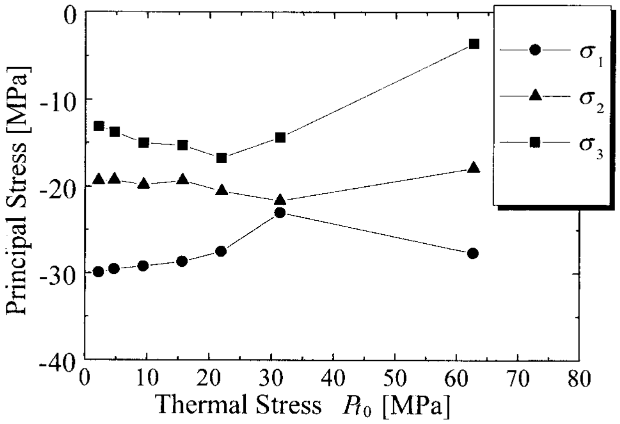
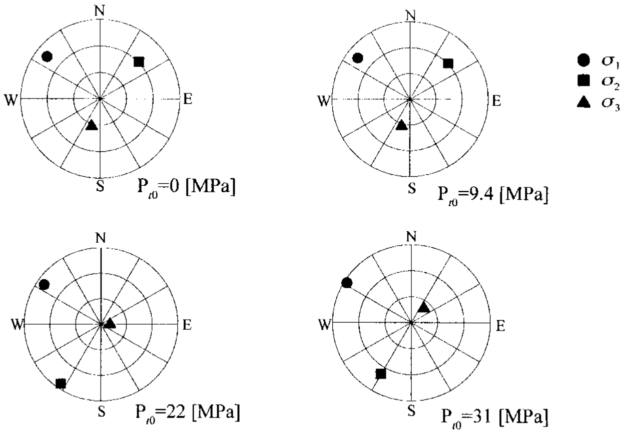


Fig. 9 Principle of drilling-induced tensile fracture (DTF) method.



(a) Magnitude of principal stress



(b) Principal axes of stress (upper hemisphere)

Fig. 10 Effect of thermal stress on the DTF method