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STRESS MEASUREMENT USING ROCK CORE IN AN HDR FIELD

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ABSTRACT

If a geothermal reservoir consists of fractures, it will be significantly important to know the stress state of the area of interest of the geothermal field because the behavior of underground fractures is greatly controlled by the in-situ stress state and any fractures could contribute to production of geothermal fluid. Two core-based stress measurement methods (DSCA and ASR) were conducted in the Hijiori HDR test site in Japan to study applicability and reliability of these methods. DSCA is considered to show a good result in aspect of principal stress directions. The E-W direction is thought to be strongly compressed at the site from the DSCA result and other investigations. Principal stress ratios estimated from DSCA fall into a reasonable range of values though there are not enough reliable data for comparison. ASR is also considered to be applicable to an HDR field, but measured anelastic strain was very small. In this ASR study, the E-W direction is estimated to be strongly compressed. This direction of major horizontal stress is also consistent with various investigations, including DSCA, for the upper reservoir. At present, DSCA is considered to be worth studying further and the ASR method needs more improvement for use in geothermal fields.

1. INTRODUCTION

The behavior of underground fractures is greatly controlled by the in-situ stress state. Hence, stress measurements are necessary to design a proper system of artificial fracture in the HDR, and to characterize conventional geothermal reservoirs where fractures are dominant. It is advisable to compare several methods that can estimate the stress state of deep and hot areas, because of the difficulties and uncertainty of such measurements. Though a stress measurement method of hydraulic fracturing is reliable and is applicable to a geothermal field, it is an expensive method, especially if it needs many trials to estimate the stress state. Core-based methods, such as DSCA (Differential Strain Curve Analysis), ASR (Anelastic Strain Recovery) method, AE (Acoustic Emission) method, DRA (Deformation Rate Analysis), PSHA (Principal Strain Hysteresis Analysis), only need oriented rock core samples to estimate the stress state and it is easy to conduct many experiments if the length of recovered rock core is enough. Core-based methods are not free from disadvantages. For example, core-based methods are not an in-situ method and the 'memory mechanism' of the in-situ stress/strain of the rock core is not elucidated enough. Two core-based methods (DSCA and ASR) were conducted at the Japanese HDR test site, Hijiori, to study applicability and reliability of these methods.

2. HIJIORI FIELD

Hijiori is an experimental field of the Japanese HDR research project conducted by NEDO (New Energy and industrial technology Development Organization). Hijiori field is located at the south edge of the inner Hijiori caldera and is several kilometers distant from Hijiori spa town. The Hijiori site has four experimental wells called SKG-2, HDR-1, 2, 3. The target hot dry rock is granodiorite and its maximum temperature is 270 °C at 2,300m depth. Oriented cores recovered from HDR-3 in 1990 and HDR-1 in 1988 were tested by DSCA. Oriented cores recovered from HDR-3 in 1993 and HDR-2 in 1994 were tested by the ASR method. Orientation equipment is conventional; that is, a coring barrel with three scribe knives and an attachable tool that measures the direction of the toolface. There are two artificially activated fracture systems in the target rock. The shallower one is called the upper reservoir. It is located at around 1,800m depth. This was developed from the beginning and was used in a 90-day circulation test in 1992. The deeper one is called the lower reservoir. It is located at around 2,200m depth. Two 30-day circulation tests have been conducted in this lower reservoir. A long-term circulation test, over one year, is planned and is going to be conducted using these reservoirs.

In Hijiori field, several researches have been done to investigate the stress state of Hijiori reservoir. Table 1 summarizes these investigations and estimated stress fields. It is seen from Table 1 that, at Hijiori site, the E-W direction is most strongly compressed in the horizontal plane. In a 3D-stress field, both a normal faulting stress regime and a slip-strike faulting stress regime could be estimated. In the lower reservoir, Tezuka and Niitsuma (1998) reported a stress regime of nearly normal faulting.

3. DSCA

DSCA can detect and estimate the orthogonal crack distribution system in a rock sample under several assumptions. Stress relief could induce this crack system while a sample was recovered. The principal stress directions and their ratio could be estimated by DSCA. Strickland and Ren (1980) proposed and named this method. Our measurement system was improved to take less time in experiment and to measure sample strains directly (Oikawa *et al.*, 1993).

3.1 Core Profile

In 1988, a production well, HDR-1, was drilled to 2,200m depth. Oriented coring was conducted three times while drilling from 2,140m to 2,200m, and three 100-mm diameter cores were successfully taken and oriented. In 1990, a production well, HDR-3, was newly drilled to 1,907m depth. Oriented coring was conducted seven times while drilling from 1620m to 1907m, and five 100-mm diameter oriented cores were also successfully taken. Thus HDR-3 cores were taken from the upper reservoir and HDR-1 cores from the lower reservoir, respectively.

3.2 Experiments

Twelve cubic test pieces were prepared for the DSCA experiment. Each sample had 24 foil strain gauges fixed on its surface and each sample was sealed with silicone rubber. Each sample was compressed hydrostatically in a pressure vessel by oil. The pressure was increased linearly from 0 to 100 MPa, and then decreased to 0 MPa. The pressure rate was kept constant at 0.025 $MPa.sec^{-1}$ by a servo-controlled system because a shortened experiment time is desirable for an accurate measurement. Both strain and pressure were measured at 0.1 MPa intervals. In our DSCA experiment, a fused silica sample for the reference was not used. The absolute value of strain of the specimen was directly used in our analysis procedure.

3.3 Analysis

When a rock specimen is compressed hydrostatically, micro cracks within it tend to close. Effects of closure of the cracks appear on pressure-strain curve as a deviation from a straight line. Strickland and Ren (1980) thought this deviation was an indicator of stress relief during in-situ coring and used it as relief strain in in-situ stress state estimation. They also used Hooke's law to estimate the in-situ stress magnitudes. A strain tensor analysis under each pressure was conducted directly from the strain measurements using a least-squares technique in our study. Each pressure-normal strain behavior of six non-parallel directions of a sample is estimated. Inclination or derivative of each curve changes as a function of pressure. This indicates the effect of crack closure. Differences between the slope in lower pressurized region and that in higher pressurized one indicate the total amount of closed crack. This difference is assumed to be proportional to relief strain when a sample was taken from deep underground. Poisson's ratio must still be assumed under the assumption that the sample rock has isotropic elastic properties. A Poisson's ratio of 0.2, based on the measurements of the physical properties of the cores, is assumed.

3.4 Results

Figure 1 shows principal stress directions of seven samples taken from HDR-3. Results of five other samples were neglected because unstable pressure-strain behaviors were obtained. The reason might be a complex crack distribution system within these core samples. Seven results show a minimum principal stress direction oriented NNE-SSW or N-S. Five results show a direction of maximum principal stress oriented E-W or ESE-WNW and inclined about thirty degrees to the horizontal plane. Table 2 shows the ratios of the principal stress magnitudes of each sample. The highest ratio is 1.0 : 0.79 : 0.56 and the lowest ratio is 1.0 : 0.90 : 0.82.

Principal stress directions of all samples of HDR-1 core show no obvious trend. Table 2 also shows the ratios of the principal stress magnitudes of each test cube taken from HDR-1. The highest ratio is 1.0 : 0.79 : 0.51 and the lowest ratio is 1.0 : 0.83 : 0.73.

4. ASR

Rock not only exhibits non-linear elasticity, but also has a nature of visco-elastic properties. After stress relief caused by in-situ coring, an obtained rock core is thought to begin dilating visco-elastically with time (Teufel, L.W., 1982). ASR measures this visco-elastic dilation of the rock sample after coring. This visco-elastic deformation is assumed to be related to the magnitude of in-situ stress relief. Therefore, the principal stress could be estimated by visco-elastic dilation measurement of the sample. ASR also could estimate the magnitude of major stresses by re-compression and re-dilation in a laboratory experiment. At present in this study, only 2D analysis of principal stress directions is applied because it is simple and it is enough to investigate the applicability to an HDR field.

4.1 Core Profile

In 1993, a production well, HDR-3, was extended from 1,900m to 2,300m. Oriented coring was conducted three times while drilling from 2,100m to 2,300m, and 100-mm diameter cores were taken. In 1994, a production well, HDR-2, was side-kicked and drilled from 1,500m to 2,300m depth. An oriented coring was conducted around 2,100m depth, and 100-mm diameter cores were successfully taken and oriented. Therefore, all of these cores were recovered from the lower reservoir.

4.2 Experiments

In both 1993 and 1994, test samples were cut out from obtained hot cores for ASR measurements. Each sample was put into a constant temperature and constant humidity chamber just after being set on ASR measurement equipment. Dilation of the sample was measured with air-suspended hi-resolution LVDTs. Dilations of six nonparallel directions on each sample were measured. Two LVDTs were arranged against each other for one measurement direction. A sample was put between these LVDTs. In this chamber, the temperature was set to 40 °C and humidity was set to 100% to prevent drying of the sample. The measurements lasted for three days. In the 1993 experiments, measured dilation data were contaminated heavily with noise induced by a change of room temperature, although the sample was set in the chamber. In 1994, the measurement system and control of outer environmental temperature was improved to avoid such noise contamination.

4.3 Analysis

The amount of dilation of the rock core sample was processed to determine anelastic strain. A term of anelastic strain is used to distinguish dilation phenomenon from ordinary inelastic behavior of rock. Anelastic strain is related to in-situ stress magnitude. In addition, directions of anelastic principal strain were assumed to correspond to in-situ principal stress directions. In this study, only directions of horizontal principal stress were estimated because the estimation procedure stayed within 2D analysis.

4.4 Results

As mentioned above, measured dilation data of HDR-3 cores were contaminated with noise induced by daily changes of room temperature. A digital low-pass filter was first used to suppress such noise. Secondly, data that had been measured at the same room temperature were used to cancel such a noise on the ASR specimen. In spite of these efforts, the expected linear increase of strain was not obtained from HDR-3 cores. On the other hand, although the measured dilation data of HDR-2 cores were also contaminated with noise induced by daily changes of room temperature, contamination of data was cleaned up enough by the procedure mentioned above. Figure 2 shows the measured anelastic strain behavior of an HDR-2 core sample. Linear increase of anelastic strain was observed after twelve hours.

Table 3 shows ASR results by 2D analysis. On HDR-3 cores, magnitudes of nondeviatoric anelastic strain are very small. This nondeviatoric anelastic strain means average dilation. Large dilation is desirable for good estimation of ASR. On an HDR-2 core, a relatively large amount of non-deviatoric anelastic strain was successfully measured. Estimated directions of major horizontal stress seemed to fluctuate. However, as a whole, it indicates that the E-W direction is strongly compressed.

5. DISCUSSION

The DSCA result from HDR-3 core generally agreed with other measurements and observations, which are shown in Table 1, in principal stress directions. The DSCA result indicates intermediate stress state between a normal faulting stress regime and a slip-strike faulting stress regime. Ratios of principal stress magnitudes fall into a reasonable range, but there are no reliable data for reference. It is difficult to determine the state of stress from the DSCA result from HDR-1 core because the data are scattered. The total number of samples was thought to be insufficient to estimate the stress field. In DSCA, if the total number of samples is enough, the analysis could be useful and applicable in an HDR field.

The ASR results from HDR-3 core were heavily contaminated with noise caused by daily changes of room temperature. In addition, the temperature of each sample was decreasing slowly during ASR measurements. This phenomenon could make the samples shrink slightly during measurement and could make the magnitude of nondeviatoric anelastic strain very small. However, although ASR results from HDR-2 core were also contaminated with such a noise, a linear increase of anelastic strain could be observed finally. This improvement was achieved by the calibration procedure and stable temperature behavior of the sample. This shows that especially careful preparation for ASR measurement is required in an HDR field. A strain of 10×10^{-6} is equivalent to a displacement of 1×10^{-3} mm in our sample. Thus an ASR measurement is very delicate and should be very precise. The estimated direction of maximum horizontal stress is E-W. This direction of maximum horizontal stress is also consistent with other investigations on the upper reservoir including DSCA. ASR could be used to estimate a stress state but further study is required for this method. In order to improve robustness, it is necessary to increase the number of measurement points or measurement directions of dilation on the sample.

6. CONCLUSIONS

DSCA was successfully applied to estimate the stress state in the upper reservoir of Hijiori HDR field. The direction of minimum principal stress is estimated as NNE-SSW or N-S. The direction of maximum principal stress is estimated as E-W or ESE-WNW and inclined about thirty degrees to the horizontal plane. This stress state is generally consistent with other investigations, such as 3D micro-seismic mapping of the reservoir. This shows that DSCA is useful in estimating directions of in-situ principal stress of a rock mass at depth even when an in-situ temperature is quite high. The highest ratio of principal stress magnitudes was 1.0 : 0.79 : 0.56 and the lowest ratio was 1.0 : 0.90 : 0.82. This ratio is thought to be reasonable but there are no other reliable and comparable data in Hijiori field.

ASR is also considered to be useful to an HDR field, but measured anelastic strain could be very small. Generally speaking, it is very difficult and expensive to prepare and conduct such a delicate measurement in the field. In this ASR study, maximum compression was along the E-W direction. This direction of maximum horizontal stress is also consistent with other investigations on the upper reservoir including DSCA. ASR is thought to require improvement in reliable measurement.

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REFERENCES

Oikawa, Y., Matsunaga, I. and Yamaguchi, T. (1993). Differential Strain Curve Analysis to Estimate the Stress State of the Hijiori Hot Dry Rock Field, Japan. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol.30 (7), pp.1023-1026.

Strickland, F. G. and Ren, N. K. (1980). Use of differential strain curve analysis in predicting in-situ stress state in deep wells. Proc. 21st. U. S. Sympo. on Rock Mech., pp.523-532

Teufel, L. W. (1982). Prediction of hydraulic fracture azimuth from anelastic strain recovery of measurements of oriented core. Proc. 23rd. U. S. National Sympo. on Rock Mech., pp.238-245.

Tezuka, K. and Niitsuma, H. (1998). Fracture system and stress estimated microseismic clusters in Hijiori HDR test site. Draft: Papers and Abstracts, International conference – 4th HDR forum, SESSION 4b.

Table1 Various stress investigation of Hijiori reservoir

Phenomena / Method	Type	Earth stress direction		
		Max.	Int.	Min.
Movement of earth crust in northeastern area of Japan	Horizontal plane	E-W	-	N-S
Lineament observation around Hijiori area	Horizontal plane	E-W	-	N-S
State of geological layer	Horizontal plane	E-W	-	N-S
Mapping of AE events occurred around reservoir	3-D	E-W~ENE-WSW	-	N-S~NNW-SSE
Focal mechanism solution of AE events	3-D	N79E	Vertical	N189E
Mapping of injection/production point of wells	3-D	-	-	N166E 20S
Fractures observed in wells by BHTV	3-D	-	-	N-S
Mapping of extension fractures observed on cores	3-D	-	-	N-S
Measurement of earth stress using cores by AE method*	Horizontal plane	N68.5W	-	N21.5E
Mapping of shear fractures observed on cores	3-D	Vertical	NW-SE	NE-SW
	3-D	NE-SW	NW-SE	Vertical
	3-D	Vertical	NE-SW	NW-SE

* Cores were oriented by fracture observation

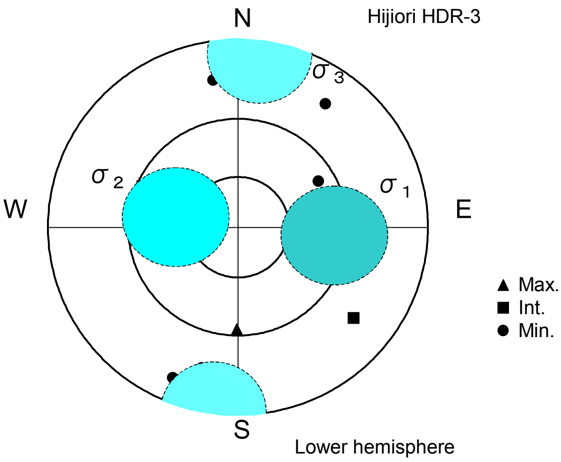

Figure 1. Estimated principal stress directions of HDR-3 core

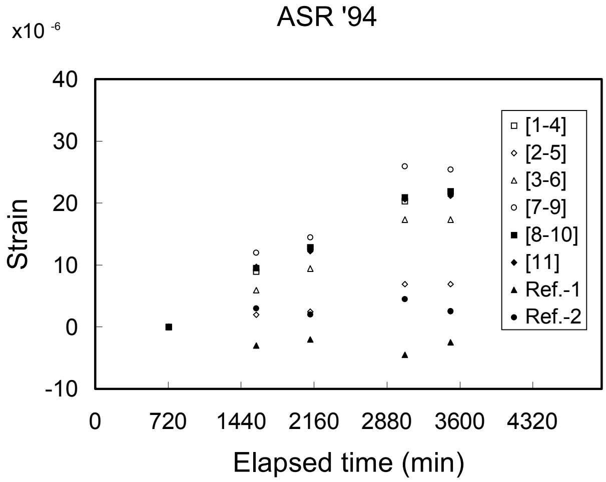

Figure 2. Measured anelastic strain on HDR-2 core

Table 2. Estimated principal stress magnitudes and their ratio by DSCA

Sample ID	Well	Depth	Ratio of principal stress magnitude*2					Principal stress magnitude*3		
								Max.	Int.	Min.
		(m)	Max.		Int.		Min.	(MPa)	(MPa)	(MPa)
HG90-2A	HDR-3	1641.2	1.00	:	0.75	:	0.57	49.4	37.2	28.2
HG90-3A*1	HDR-3	1717.4	1.00	:	0.70	:	0.59	49.3	35.5	28.9
HG90-4B*1	HDR-3	1718.4	1.00	:	0.89	:	0.76	43.2	38.5	32.8
HG90-5B	HDR-3	1741.8	1.00	:	0.79	:	0.56	41.4	32.7	23.4
HG90-7A*1	HDR-3	1758.1	1.00	:	0.96	:	0.77	42.3	40.5	32.5
HG90-7B*1	HDR-3	1758.1	1.00	:	0.90	:	0.82	44.2	39.6	36.1
HG90-8A*1	HDR-3	1903.9	1.00	:	0.88	:	0.75	46.5	40.8	34.9
HG88-2A	HDR-1	2140.6	1.00	:	0.85	:	0.51	72.0	61.4	36.7
HG88-2B	HDR-1	2140.6	1.00	:	0.83	:	0.73	52.4	43.5	38.5
HG88-3A	HDR-1	2180.2	1.00	:	0.79	:	0.51	75.2	59.8	38.5
HG88-3B	HDR-1	2180.2	1.00	:	0.85	:	0.64	58.9	49.8	37.7
HG88-4A	HDR-1	2204.5	1.00	:	0.70	:	0.61	64.8	45.0	39.4

*1: Marked samples are used to calculate an average of ratio of principal stress of HDR-3.

*2: Maximum principal stress magnitude is equal to one.

*3: Magnitudes are estimated under an assumption that overburden pressure is equal to vertical s

The overburden rock density is supposed to be 2.3g/cm^{-3} from surface to 1500m depth and to

Table 3. Estimated directions of major horizontal stress with ASR method.

Sample ID	Well	Depth	Time from coring to start of measureme	Time from coring to origin point of analysis	Appearent measure-ment time for ASR	Non-deviatoric anelastic strain	Direction of major horizontal stress
		(m)	(hour)	(hour)	(hour)	(10^{-6})	
HG93-1A	HDR-3	2101.6	11	23	36.3	0.4	N140E
HG93-1B	HDR-3	2101.7	11	23	36.3	2.2	N100E
HG93-3A	HDR-3	2252.9	21	38	22.9	0.7	N76E
HG93-3B	HDR-3	2553.6	18	35	22.9	0.4	N67E
HG94	HDR-2	2107.5	18	30	47.5	15.3	N125E