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APPROACH TO THE ESTIMATION OF GEOTHERMAL RESERVOIR PERMEABILITY BY TECTONIC SIMULATION

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ABSTRACT

Through assuming a model of the geologic structure development processes of geothermal field, numerical experiments have been conducted by employing the three-dimensional elasto-plastic finite element method based on the virtual basement displacement method. These experiments have enabled us to achieve analyses of stratigraphic displacement, strain and stress, as well as fracture systems. Then, we studied relations between the data obtained by our analyses and water permeability.

As a result of the study, it was observed that the output fracture systems very closely represent the fault systems estimated from surface mapping. Also, satisfactory correlative relations have been clarified between the strain amount and the hydraulic conductivity collected from the drill hole data. Consequently, the conclusion has been reached that numerical analysis through employing this type of tectonic simulation technique seems highly effective to achieve evaluations of fracture-type geothermal reservoirs.

INTRODUCTION

Evaluation of reservoirs where geothermal fluid accumulates and clarification of the mechanism of hydrothermal flow that supplies heat to the reservoirs are important problems presently being confronted in connection with activities ranging from exploration to exploitation of geothermal resources. Regarding the first problem, the evaluation of geothermal reservoirs, the targets and objectives of evaluations differ depending on the exploitation processes. In other words, in the initial stage of exploration and exploitation, the problem involved is related to the estimation of reservoir positions and the prediction of reservoir scales.

On many occasions, fractures in the form of faults or joints existing in geothermal fields have been reported to play the role of forming paths for geothermal fluid or creating reservoirs. Therefore, in attempting to achieve an effective exploration of geothermal resources or conducting an accurate evaluation of geothermal reservoirs, an important problem is the clarification of scales and shapes of areas where fractures developed. On the other hand, a correct comprehension of deep-stratum geologic structures and the actual fracture systems involves immense difficulties. Thus, in the industry today, effective exploration techniques to facilitate such comprehension are being strongly demanded.

In recent years, the advancement of large-capacity computers has resulted in introducing the technique of numerical experiments into the field of geology. Consequently, various simulation methods are being applied to analyses of geological structures. Under such circumstances, Nakano et al. (1983) support the fact that tectonic simulation techniques involving numerical experiments or other methods are highly effective not only for studies of deep-stratum fracture systems, but also for evaluations of geothermal reservoirs (Ito et al., 1985).

The study results reported in this paper reflect the above-mentioned background status. Namely, revealed are analytical results on fracture systems by conducting numerical experiments through employment of a three-dimensional elasto-plastic finite element method based on the Virtual Basement Displacement method (Kodama et al., 1985). The location selected as a model area is the geothermal field in the north of Hachimantai. Our experiment also included a study on relations between the water permeability of drilled wells and strains presumed to exist by numerical experiments.

In conducting the study, the authors owe a supply of geological data in the model area to courtesy of the Geothermal Energy Development Dept. of Mitsubishi Metal Corp., and wish to express their appreciation to Mr. Y. Sakai, Director of the Dept., for his useful discussion.

NUMERICAL EXPERIMENT METHOD

Figure 1 is a flow chart of the virtual basement displacement method. The employed experimental processes can be classified into two categories; one is modeling of the geologic structure development processes of the subject area, and the other pertains to numerical simulations of these development processes. In the former category, conducted were geological/stratigraphic studies of various exploration data followed by an estimation of the historical structure development of virtual basements. As for the

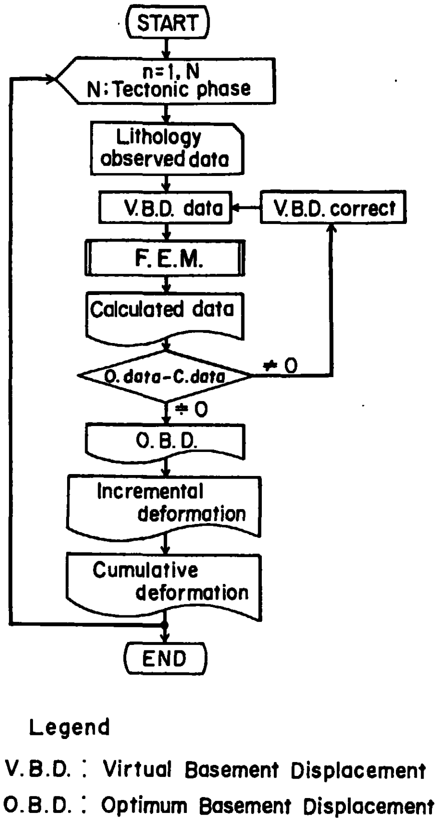


Figure 1. Flow chart of Virtual Basement Displacement method

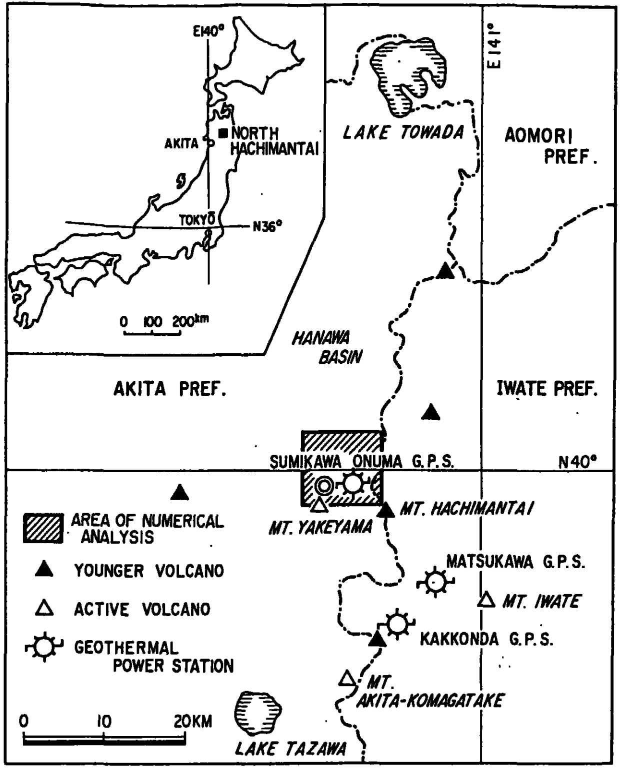


Figure 2. Location map of the North Hachimantai geothermal area

latter category, we applied calculations of stress, strain, and plasticity zones during the course of displacement simulation of the modeled basements.

GEOLOGICAL STRUCTURE OF MODEL AREA

Outline of Geological Structure

The north Hachimantai area, situated in Akita Prefecture in the northeastern district of Japan, is one of the nation's most active geothermal zones where a widespread distribution of geothermal manifestations exists involving hot springs, spouting steam, and other phenomena resulting from Quaternary-period volcanic activities. Presently, the Onuma Geothermal Power Plant (10MW) is in operation, and in the adjoining Sumikawa area, a 50MW geothermal power plant is being constructed (Fig. 2).

As shown in Figs. 3 and 4, according to Yora et al. (1973, 1977), the geology of the subject area is primarily composed, from the lowest stratum upward, of sedimentary rocks or volcanic rocks of Monzen, Daigima, Nishikurosawa, Onnagawa, and Funakawa of the Neogene stage. On top of these stages, overlaid are younger volcanic rocks and lake deposits of the Quaternary period.

In terms of geological structure, the model area is located on the western edge of the Hanawa subsidence zone that stretches from the Hanawa Basin in the north to Lake Tazawa in the south. The eastern edge is bordered by the Senosawa upheaval zone, and the western side is bounded by Hanawa faults. Further, it can be said that the model area rests on a localized upheaval within the graben structure.

Regarding the fault structure, as is evident from Fig. 5, predominantly existent are NW-SE faults and N-S faults, including the N-S trending Propylite fault situated in the central portion of the subsidence zone.

Development Processes of Geological Structures

Geological structures of the model area can be considered to have developed as illustrated in Fig. 6. During the Nishikurosawa age, the sedimentary basin extending in the N-S direction must have been formed, which is then believed to have been followed by continued formation of a subsidence zone during the subsequent Onnagawa age. It can be further conceived that block movements of basements must have occurred at the same time, and that correlative upheavals and subsidences must have restructed the sedimentary basin, having caused the Onuma area to develop localized upheavals. Similarly to the Onnagawa age, upheavals/subsidences are believed to have continued through the Funakawa age. During this period, however, some parts must have been upheaved above the sea level. This land formation must have expanded to cover the entire area during the subsequent Quaternary period. Also, during this period there must have been a formation of the fold structure possessing an axis in the N-S direction.

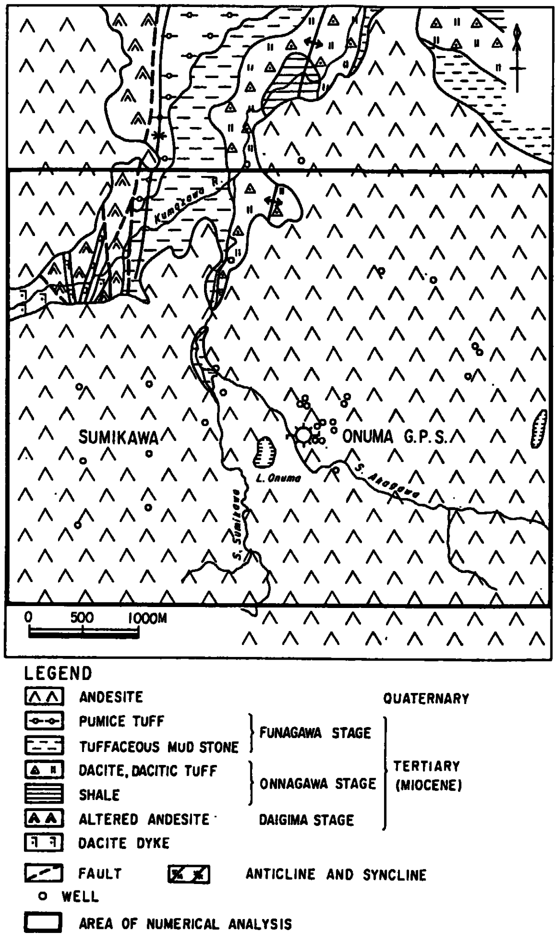


Figure 3. Geologic map of the North Hachimantai geothermal area (after Yora et al., 1973)

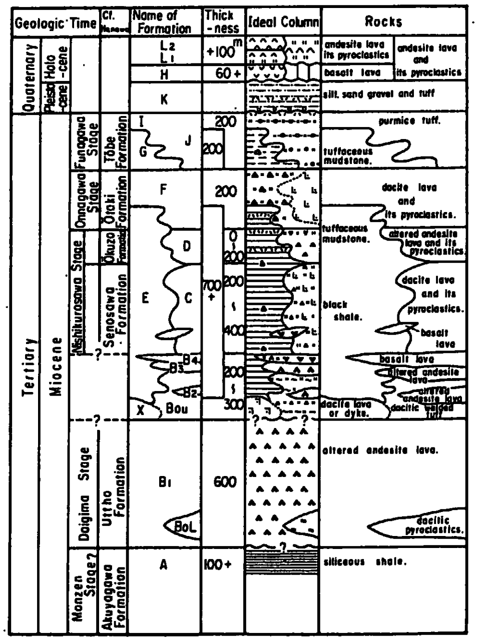
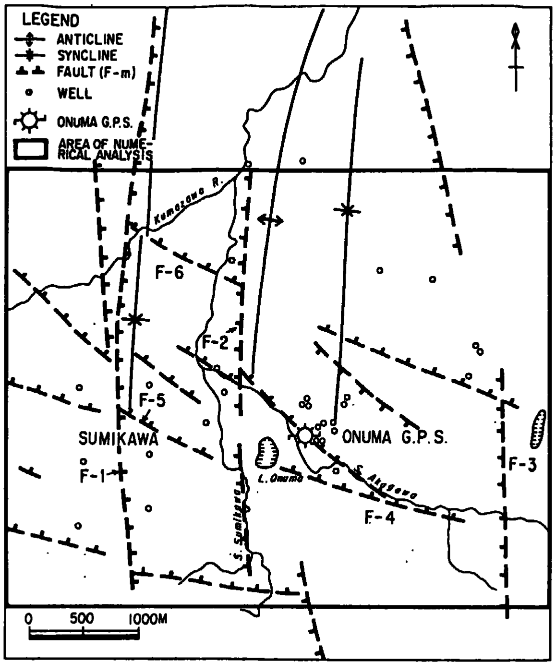
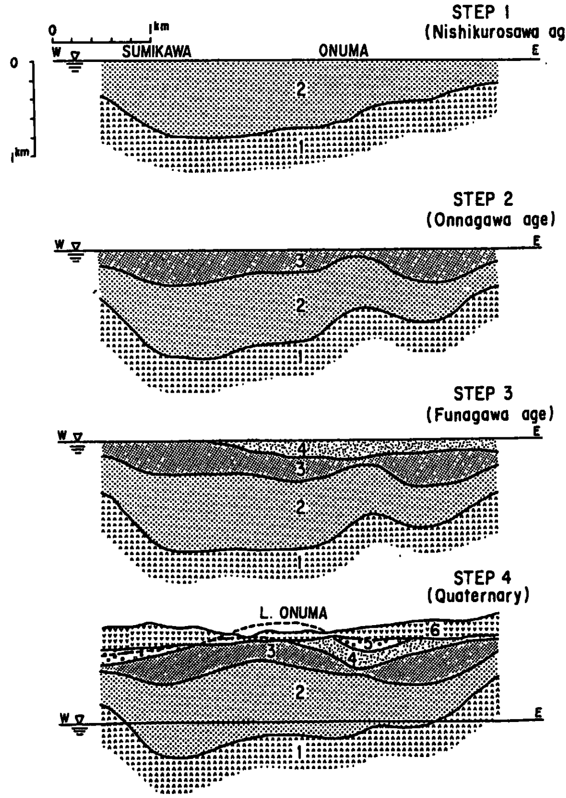


Figure 4. Stratigraphic columnar section of the North Hachimantai geothermal area (after Yora et al., 1977)



F-1: Propylite fault, F-2: Onuma fault, F-3: Komonomori fault
F-4: Akagawa fault, F-5: Sumikawa fault, F-6: Akagawan-onsen fault

Figure 5. Tectonic map of the North Hachimantai geothermal area (after Yora et al., 1977)



1. Daigima stage 2. Nishikurosawa stage 3. Onnagawa stage
4. Funagawa stage 5. Quaternary lake depo. 6. Quaternary volcanic rocks

Figure 6. Geologic profile for each geologic age (after Ando et al., 1985)

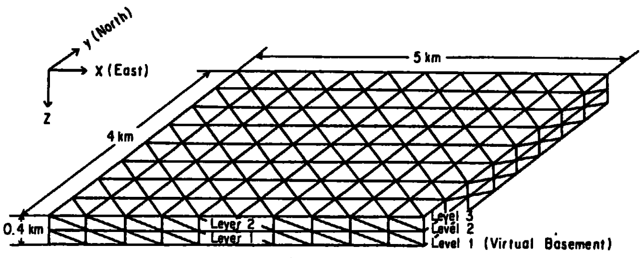
NUMERICAL EXPERIMENTS

The virtual basement displacement method (Kodama et al., 1984) is a type of inversion method. In other words, by preliminarily assuming the basement movement, deformation of upper-layer strata caused by this movement is experimentally reproduced. By this method, the displacement amounts of virtual basements are regulated until differences between the reproduced results and the observed facts are minimized, thereby obtaining the optimum basement displacement. This step is conducted for each sedimentary stage, incremental deformation of basements in respective ages is clarified, and then by accumulating resultant data, analyses are achieved on geological structure formation processes up until today.

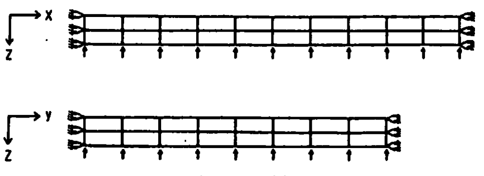
In the selected model area, experiments were conducted on the geological structure development processes by dividing them into the following four steps. In presuming displacement amounts, the uppermost layers that existed in respective ages were assumed to be the sea level, while the restoration of ancient environmental conditions and the horizontal shift of strata were not subjected to our consideration.

Step 1: Deformation that developed during Nishikurosawa age
Step 2: Deformation that developed during Onnagawa age
Step 3: Deformation that developed during Funakawa age
Step 4: Deformation that developed during Quaternary period

Figure 7 shows primary conditions under Step 1, the element division diagram, and displacement restraining conditions at boundaries. On the other hand, Table 1 lists the numbers of layers, nodes, and elements for respective steps. Also, revealed in Table 2 are the lithological properties.



Primary condition (Step I)



Boundary condition

The primary tectonic system is composed of two layers, each layer divided into eighty rectangular cells. Each cell is subdivided into six tetrahedral elements. The nodes on and within the tectonic system can move freely except for lateral movement on the side wall of the system.

Figure 7. Primary and boundary condition of the tectonic system

Table 1. Table of experiment system sizes

Item Age	Layer	Node	Element
Step 1	2	297	960
Step 2	6	693	2880
Step 3	8	891	3840
Step 4	9	990	4320

Table 2. Table of physical parameters

Item Rock	Confining pressure $X10^6$ g/cm^2	Young's modulus $X10^8$ g/cm^2	Poisson's ratio
Daigima stage	1.5	3.0	0.25
Nishikurosawa stage	0.6	0.5	0.28
Onnagawa stage	0.7	0.5	0.28
Funakawa stage	0.7	0.4	0.30

RESULTS OF NUMERICAL EXPERIMENTS

Among the calculation results, Fig. 8 shows the distribution of strains and fracture systems of Layer 1 in each step; Fig. 9 represents a bird's-eye view of optimum basements for respective steps (Ando et al., 1985). It is evident that the highly strained zones run in the N-S direction from the Kumazawa River at the northwestern edge of the area as far as to the Sumikawa district at the southwestern area. At the same time, these strained zones reveal a continuous stretch in the NW-SE direction from the Kumazawa River over to the Onuma district in the center portion of the area. It can be said that the fracture systems presumed from the principal stress distribution in the high-strain areas closely represent the known fault structures (Fig. 5).

RELATIONS BETWEEN EXPERIMENTAL RESULTS AND WATER PERMEABILITY

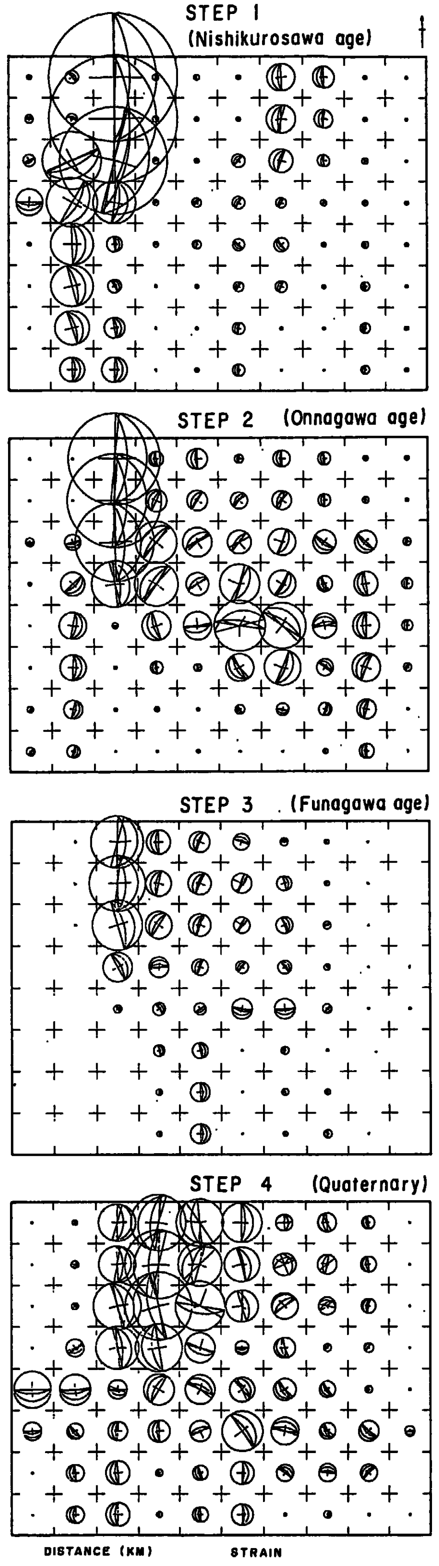
Water permeability of strata is believed to be closely related to the fractures. Since such fractures are assumed to be formed at areas where strain is intense, we have studied mutual relations between the said two factors by comparing the distribution of circulation loss of drill mud and hydraulic conductivities with the strain amounts obtained from the experiments.

Circulation Loss and Strain Amounts

The circulation loss was classified into the following three levels, and comparative studies of these levels were effected against the strain amounts of blocks encountered with circulation loss.

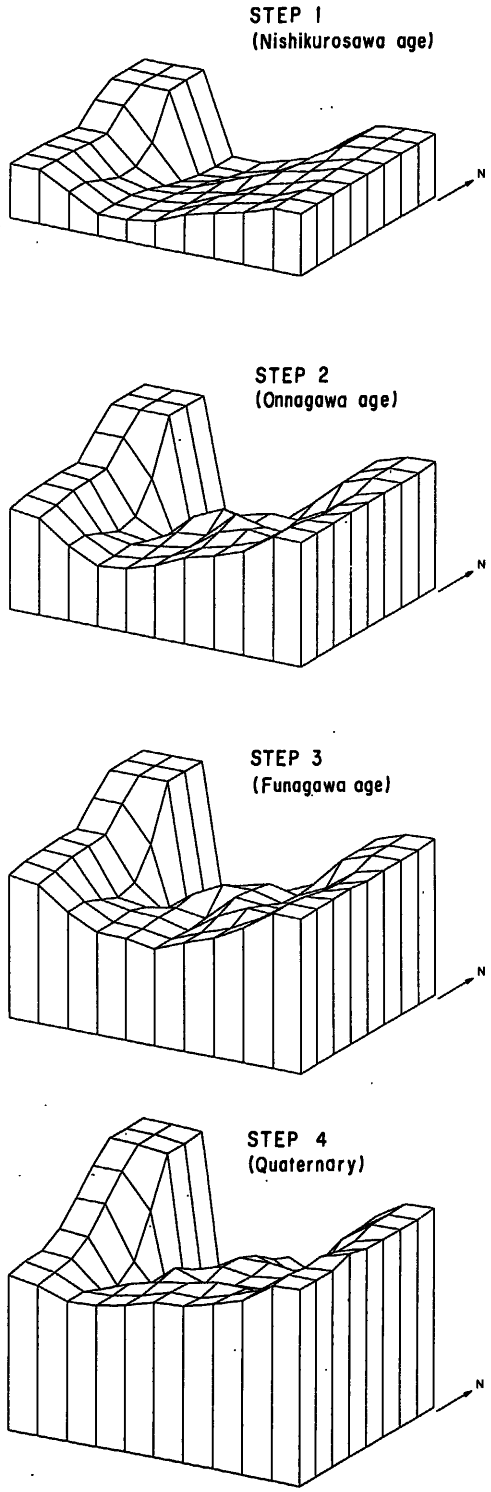
Level "0": No circulation loss of water
Level "1": Partial circulation loss of water
Level "2": No water return

Scales of circulation loss seem to reveal a positive proportionate relation with the strain amounts, especially this relation being conspicuous under Step 4 (Fig. 10). Accordingly, the formation of highly permeable layers can be judged to receive the most intense influences by structural movement that occurred during the Quaternary period.



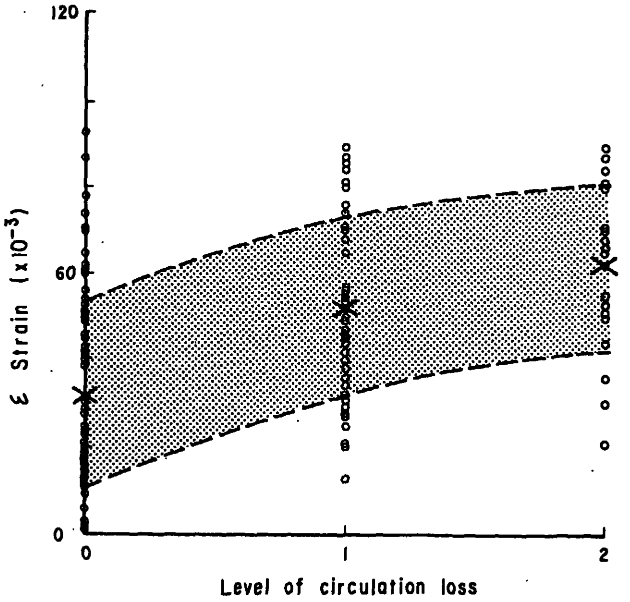
Fractures are shown on the upper hemisphere of Wulff's net presuming that the angle of shear is 40°. The radius of a circle represents the magnitude of the strain.

Figure 8. Strain and fracture in the first layer (after Ando et al., 1985)



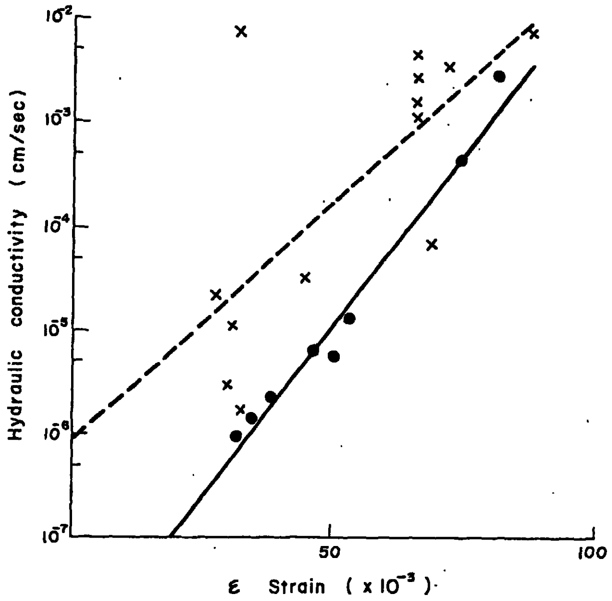
The basement is shown by the bird's-eye view when the deviation is 30° and the dip is 20°.

Figure 9. Optimum basement for each geologic age



Level 2: No water return, Level 1: Partial circulation loss,
Level 0: No circulation loss, X: Average strain of elements intersected by layers of circulation loss, ▨: Strain range with $\bar{\varepsilon} \pm \sigma$

Figure 10. Strain versus the level of circulation loss



Hydraulic conductivity is estimated mainly from injection tests for wells.
Strain is in the cell in which the main circulation loss is encountered.
●: Cell whose horizontal stress component is shear
x: Cell whose horizontal stress component is tension

Figure 11. Strain versus hydraulic conductivity

Hydraulic Conductivities and Strain Amounts

Also subjected to our study were relations between strain amounts and logarithmic conversion values of hydraulic conductivities. The hydraulic conductivities displayed positive proportionate correlations with the strain amounts under Step 4 (Fig. 11).

Regarding Fig. 11, we are able to note that the correlative relations between the two factors are closer under compression stress than under tension stress field. These closer correlative relations under compression stress are believed to have been caused by the fact that diversification per each fracture is minimal, because numerous fractures develop under compression stress. On the other hand, open-type fractures created under tension stress display rather wide diversification per fractures pertaining to their widths and quantities.

As explained above, the existence of positive proportionate correlative relations is clearly evident between water permeability and the strain caused by basement movement during the Quaternary period. Consequently, it can be considered possible to achieve, up to certain levels, an estimation of water permeability from the status of strain clarified by the numerical experiments. However, when applying the numerical experiment results to evaluate the underground water permeability, it is essential to combinedly consider not only the relations between strain and water permeability, but also the differences of lithological properties per elements and historical variations of stress fields.

CONCLUSIONS

Results of our study reported herein can be summarized as follows.

- By conducting the numerical experiments through employing the virtual basement displacement method, the strained zones extending in the N-S and NW-SE directions were detected. Further, the fracture system estimated from the stress field revealed close coincidence with the trend of strained zones.
- The distribution and trend of the fracture system clarified by the numerical experiments is considered to closely represent the fault structures already estimated from the surface mapping.
- Scales of the circulation loss possess very close correlative relations with strains especially resulting from the basement movement that occurred during the Quaternary period. Consequently, the formation of highly permeable zone can be considered to have been most intensely influenced by structural movement during the Quaternary period.
- It is judged possible to a certain extent to evaluate the underground water permeability as well as its distribution based on strain distribution calculated by the numerical experiments. In this case, however, differences of lithologic properties per districts and variations of stress fields must be combinedly considered.

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