INVERSE PROBLEM OF ESTIMATING SOME OF THE GEOTHERMAL RESERVOIR CHARACTERISTICS (PART 1)

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In order to estimate unknown parameters describing the reservoir characteristics such as permeability and porosity, past production data (pressure, flow rate, etc.) are simulated. These properties are generally determined as those that produce the best reasonable match of the observed and calculated data at specified observation points. This process of reservoir parameter estimation is widely known as history matching and has been studied extensively in petroleum engineering and hydrology during the last two decades.

The problem of history matching is basically a nonlinear optimum minimization problem and is expressed as a nonlinear operator equation of the form Ka=u, with the predicted values (pressure etc.) subject to the constraint of the reservoir model, where "a" represents the reservoir parameters, "K" is the operator representing the reservoir model, and "u" is the observed data of the model's output, such as the well pressures.

The history matching problem is precisely the inverse problem to the above equation - i.e., given "u" and "K", estimate "a". However, obtaining a unique solution of "a" given "u" for operator "K" of spatially varying parameter reservoir models is an extremely difficult problem . The standard history-matching approaches of spatially varying parameters often lead to an ill-posed problem, which is generally characterized by the nonuniqueness and instability of the estimated parameters.

Various optimization techniques have therefore been developed to circumvent the ill-posed problem and to perform minimization. They include minimax and linear programming, quasilinearization, optimum control approach, Kalman filtering method, maximum likelihood estimation, etc.

Lee, Kravaris and Seinfeld (1985, 1986) have recently shown that the regularized estimation method in minimization alleviates the ill-conditioning resulted from the conventional least-squares estimation.

Their technique is based on bicubic spline interpolation of permeability and porosity distributions and a regularization formulation to estimate permeability or porosity in a single-phase two-dimensional areal reservoir from pressure data.

However, these techniques on reservoir parameter estimation have been developed in the field of petroleum and groundwater, and their applications to geothermal reservoirs seem to be rare, because the behavior of geothermal reservoirs is more complex than that of petroleum and groundwater. We will review some techniques on reservoir parameter estimation as a inverse problem, and apply the technique developed by Lee, Kravaris and Seinfeld(1986) to geothermal reservoirs.

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TWO-PHASE FLOW PHENOMENA IN A GEOTHERMAL RESERVOIR

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INTRODUCTION

The fluid in a water-dominant geothermal reservoir is generally compressed water. When it is sent to the electric power station, it flashes in the reservoir or a well. Accordingly, the fluid consists of two phases of vapor and water in the power station. Among them, only the vapor is used for the electric power generation except the binary system. The vapor sent to the generator is generally gathered from several wells. The properties of the vapor of each well changes as a function of the wellhead pressure as well as the reservoir pressure. For instance, the drop of wellhead pressure relates to the increase of flow rate and the decrease of temperature. The degree of the change depends upon the properties of the geothermal fluid. In some case, the vapor may separate in the reservoir. The flashing point, where the vapor forms its own phase in the geothermal fluid, is dependent on the wellhead pressure and the reservoir one. The control of the wellhead pressure is, therefore, very important to optimize the power generation process. We have been examining the two-phase flow phenomena as one of the fundamental studies for the optimization. The Onikobe geothermal field is a suitable place to know the relation between the wellhead pressure and the flashing point. This report is a part of the results.

ONIKOBE GEOTHERMAL FIELD

The Onikobe caldera is located 60 km north-northwest of Sendai, northeastern Japan. The diameter is about 10 km. The Onikobe geothermal field is localized in the southeast quarter of the caldera. The field is briefly outlined by Fujita and Suzuki (1985), and is discussed especially on the viewpoint of the geothermal structure by Abe (1985). Yamada (1988) recently describes the detailed geology of the caldera. The following statement is the brief summary of them.

The field is widely covered by volcanic sediments uncomformably overlying the Pre-tertiary granitic basement (Figs. 1 and 2). The volcanic sediments are divided into six units; Kanisawa formation, Sannozawa formation, Akazawa formation, Miyazawa formation, Takahinata dacite, and Iwanazawa formation. The Kanisawa formation of Miocene age is found in drilling cores (Fig. 2). It consists of andesitic lava, tuffaceous siltstone and sandstone, tuff and tuff breccia. The Pliocene Sannozawa formation consisting of tuff is uncomformably distributed around the Kanisawa formation in the north western quarter of the caldera. It is also observed in drilling cores near the power station, though not shown in Fig. 2. The Akazawa formation overlies comformably the Sannozawa formation. It is composed of tuffaceous mudstone and tuff breccia. The lower horizon of this formation is characterized by thick andesitic lava, agglomerate and tuff. For this reason, the horizon is particularly named as Oofukazawa andesite member. Several beds of mudstone are intercalated in this member. The Miyazawa formation consists of pumice tuff, sandy tuff and dacitic tuff. The Takahinata dacite, two specimens of which give 0.25 Ma and 0.35 Ma in radiometric age, is a product of the youngest volcanic activity in this area. The present geothermal heat is considered to be given by the residual magma in this activity. The Iwanazawa formation is the youngest sediments except fan, terrace and stream ones. It is composed of mudstone, sandstone and conglomerate. The sediments from the Akazawa formation to the Iwanazawa one were deposited in a caldera lake or lakes.

A clear boundary of electric resistivity is observed as shown in Fig. 2. The resistivity of the shallow zone is less than 20 ohm-m, while that of the deep basement is more than 100 ohm-m. The boundary is not always parallel to the folding structure of the sedimentary rocks. According to the electric resistivity, the horst is located beneath the power station. This location coincides with the anticlinal axis of the Oofukazawa member (Fig. 2).

Two geothermal reservoirs are recognized (Fig. 2). The shallow reservoir is localized in the Oofukazawa andesite member above the horst. The average elevation is 300 m above the sea level. The reservoir belongs to the fracture-type. The caprock is alteration clay. The deep reservoir is located approximately -500 m. It also belongs to the fracture-type. The host of the reservoir is the green rocks of the Kanisawa formation. The reservoir occurs in the electric basement (Fig. 2). The fluid for the power generation is supplied mostly from the deep reservoir.

Two reservoirs are different in the geothermal properties. The deep reservoir is water-dominant. The vapor/water ratio after the separation is about 1/4. The chemistry of the fluid varies in places. The fluid approximately beneath the power station is acidic, and rich in chloric ion. On the other hand, the fluid obtained from incline wells are neutral. The shallow reservoir is relatively vapor-dominant. The vapor/water ratio is about 1/1. The fluid is neutral. It seems to be the vapor that separates from the deep reservoir, and that is trapped again at shallow levels.

TWO-PHASE FLOW PHENOMENA

Fig. 3 shows the relation between the elevation (above the sea level) of the feed point and the reservoir pressure of each well. Except the KR series, the reservoir pressure increases linearly with the depth. It is concluded, therefore, that all wells except the KR series drill through the same aquifer.

Fig. 4 shows the relation between the wellhead pressures and the flow rates of Wells 128 and 129. The flow rate of each well increases linearly with the decrease of the wellhead pressure.

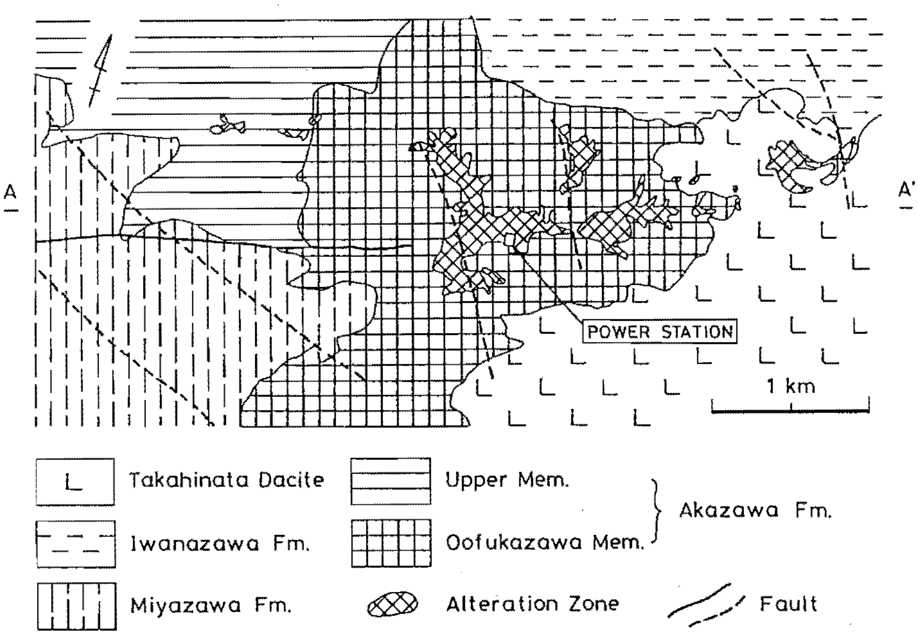

Fig. 1. Geological map of the Onikobe geothermal field.

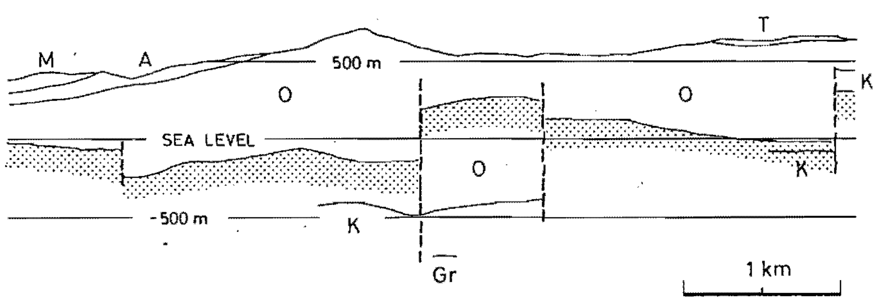

Fig. 2. Geological W-E profile of the Onikobe geothermal field. Abbreviations of geological units: A=Akazawa formation, Gr=Granitic basement, K=Kanisawa formation, O=Oofukazawa andesite member, and T=Takahinata dacite.

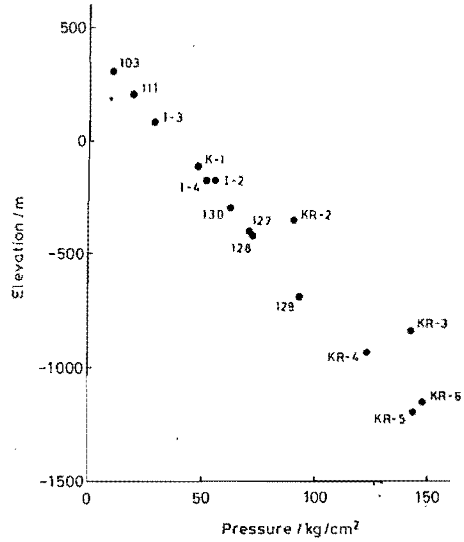

Fig. 3. Relation between the elevation (sea level) and the pressure (absolute) of the main feed point of each well.

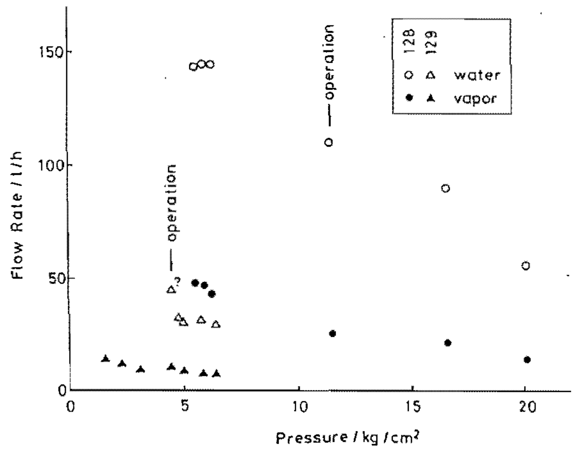

Fig. 4. Relation between the wellhead pressures and the flow rates of Wells 128 and 129.

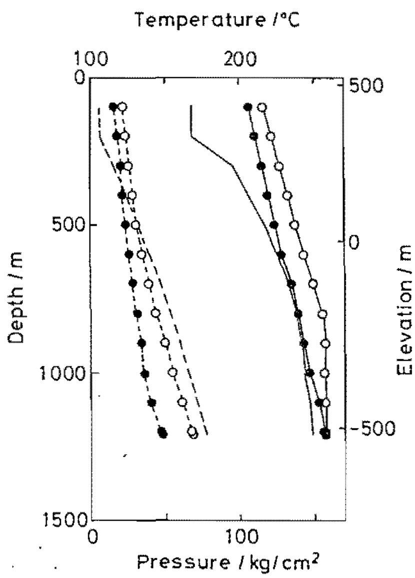

Fig. 5. Pressure (dashed lines) and temperature (solid lines) of Well 128. The lines with solid and open symbols represent the cases that the wellhead pressures are 16.6 kg/cm^2 and 20.1 kg/cm^2, respectively. The lines with no symbol represent the static condition.

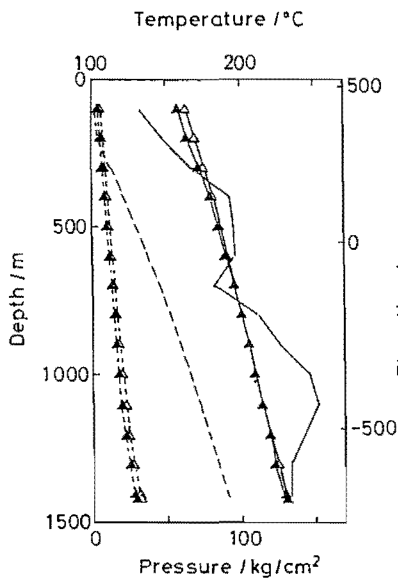

Fig. 6. Pressure (dashed lines) and temperature (solid lines) of Well 129. The lines with solid and open symbols represent the cases that the wellhead pressures are 5.0 kg/cm^2 and 6.9 kg/cm^2, respectively. The lines with no symbol represent the static condition.