THE RESISTIVITY OF POROUS PARTLY-SATURATED MEDIA

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ABSTRACT

Experiments have been made with artificial porous media and volcanic rocks to check the empirical relationship which describes the variation of their resistivity ρ as a function of the saturation fraction S_w of an electrolyte of resistivity ρ_w, retaining porosity ϕ, fluid resistivity ρ_w, and the apparent formation factor F_a as parameter. The studies show that the relationship:

$$\rho = \rho_w F_a S_w^{-m}$$

holds up to a critical de-saturation fraction S_{wc}.

Assuming that in a vapor-dominated system the average apparent formation factor of a condensate layer and deeper 2-phase reservoir is nearly constant, these results can be used, in conjunction with resistivity sounding data from the Kamojang Field, to deduce a saturation fraction of $S_w \simeq 0.35$ for this 2-phase reservoir.

INTRODUCTION

The gross structure of the Kamojang geothermal field, West Java, was initially outlined by DC - resistivity measurements (Hochstein, 1976). These studies showed that the structure of the field is similar to the idealized vapor-dominated system proposed by White et. al. (1971). At Kamojang a deeper 2-phase (hot water/steam) reservoir is capped and mantled by a 200 to 500 m thick layer of acid condensates with true resistivity of 2 to 5 Ωm; the deeper 2-phase reservoir exhibits true resistivities above 10 Ωm. A similar resistivity structure has been found by the author during surveys of other Indonesian vapor-dominated systems (Bali, Darajat, and Salak).

The resistivity sounding (VES) curves of the first survey of the Kamojang field were interpreted by computing a set of best fit master curves (Hochstein 1976) but this method did not determine accurately the true resistivity of the deeper 2-phase substratum. With new direct inversion techniques (Zhody 1975, for example) it is now possible to obtain more reliable values for the resistant substratum. The method has recently been used to analyse some of the additional soundings made at Kamojang in 1980 (C.J. Bromley, pers.comm) and to re-interpret the older soundings. It was found that the true resistivity of the 2-phase substratum down to at least 800m depth is about 30± 10 Ωm.

Since there is little evidence to suggest that the conductance of the electrolyte and that of the rocks changes sharply at the single phase/2-phase boundary, one can postulate that the change in true resistivity of about one order of magnitude is caused by the replacement of same fraction of conductive electrolytes by non-conductive steam.

Resistivity of a partly saturated, porous medium

An empirical relation between the resistivity ρ of a porous medium, filled with an electrolyte of resistivity ρ_w as a function of the fraction of saturation S_w (i.e. the fraction of the total pore volume filled by the elctrolyte) has been given by Keller and Frischknecht (1966):

$$\rho = \rho_w F S_w^{-m} \tag{1a}$$

where F is the formation factor and m a constant. If the rock matrix (resistivity of rockmatrix $= \rho_c$) is almost non-conductive (i.e. $\rho_c \simeq \infty$) and this is true of fresh volcanics, and clean sandstones, F can be expressed by another empirical relation:

$$F = a \phi^{-n} \tag{2}$$

where a and n are constants depending on the rocktype, and ϕ is the average porosity (Archie's Law; refer to Keller and Frischknecht 1966):

If the resistivity of the rocks matrix is low, which is true of altered volcanics due to the presence of conductive clay minerals, F in equation (1a) can be replaced by the apparent formation factor Fa, which, according to Worthington (1975), can be define-d as:

$$1/F_a = 1/F + \rho_w/\rho_c \tag{3}$$

This simple equation holds as long as $\rho_w > 1\,\Omega m$ (Worthington 1975), a condition which applies for electrolytes in vapor-dominated systems. In the general case of a partly saturated medium with matrix resistivity ρ_c, equation (1a) can therefore be expressed by:

$$\rho = \rho_w F_a S_w^{-m} \tag{1b}$$

Keller and Frischknecht (1966, p. 28) state that the exponent m in equation (1a) (and presumably also in equation (1b)) "has a value of approximately 2", and that the relationship holds until the saturation fraction S_w reaches a critical value

S_{wc}. For $S_w < S_{wc}$, further desaturation will break the continuous film of electrolyte in interconnecting voids, resulting in a significant increase in resistivity to current flow. For $S_w < S_{wc}$ equation (1a) can be replaced by:

$$\rho = b\, \rho_w\, F\, S_w^{-m'} \tag{4a}$$

where b is a constant (<1) and the new exponent m' has a value of about 4-5. Keller and Frischknecht (1966, p.30) also state that S_{wc} is about 0.25 for sandstones and rocks of similar permeability, but may be as high as 0.7 to 0.8 in igneous rocks(!). Although the case of desaturated rocks with significant matrix conductivity is not cited in Keller and Frischknecht, one can postulate that for this, equation (4a) should be of the form:

$$\rho = b\, \rho_w\, F_a\, S_w^{-m'}. \tag{4b}$$

It was the last part of the statement of Keller and Frischknecht (i.e. that S_{wc} in igneous rocks might be as high as 0.7 to 0.8) and the uncertainty whether equations (1b) and (4b) hold for altered volcanics, which, for example, make up the reservoir rocks in the Indonesian vapor-dominated systems, which lead us to a series of experiments which are described in the following.

Laboratory Measurements of resistivity of partly saturated, porous media.

Initially we started with an artificial porous medium, composed of crushed and sieved quartz grains (angular and rounded) with a grain-size of 1 - 2 mm. These grains were filled in a glass vessel of known volume and successively saturated during separate steps with an NaCl solution (0.005N to 0.1N). The equipment has recently been described in a paper by Lawton and Hochstein (1980). All experiments were made at room temperature and no changes in temperature were considered since the conductance variation of an Na Cl solution with temperature is well known. The resistivity of the artificial sample was measured retaining the resistivity of the electrolyte as parameter for various fractions of saturation S_w (i.e. either by free draining of the sample or by using a vacuum pump). Hence, the conductive electrolyte was successively replaced by a non-conducting gas (air). Using the procedure described by Worthington, the matrix resistivity could be determined; this was lower than expected but significantly greater ($\rho_c \geq 1000\,\Omega m$) than that of the volcanics used later on. The simple experiment confirmed the results cited in Keller and Frischknecht (1966), namely that for media with $F \approx F_a$:

a) the value of the exponent m in equation (1a) is 2.0±0.1 for $S_w > S_{wc}$;

b) that S_{wc} for an artificial medium of quartz within the porosity range 0.39 > ϕ > 0.43 is about 0.20 (i.e. 20%);

c) from one set of data only it was found that the value of the exponent m' in equation (4a) is about 4 for $S_w < S_{wc}$.

The same experiment was repeated using finely crushed (2-3 mm) grains of slightly altered rhyolite (Ohaki Rhyolite, Broadlands, N.Z.) as rock matrix. The rock matrix was conductive (ρ_c = 200 to 400 Ωm). Some results of this experiment (for concentrations of 0.05N and 0.01N NaCl solutions) are presented in Fig. 1. An analysis of the data showed that there were no significant variations in comparison with the earth experiment although F_a differed significantly from F. Although this experiment indicates that equations (1b) and (4b) hold in the case of a conductive rockmatrix, additional experiments for a range of values of ρ_c are required before this can be confirmed. The value of S_{wc} was again the same (i.e. $S_{wc} \simeq$ 0.2) as that found previously.

In a third experiment, m and Swc were determined on cores of Ohaki Rhylite with an average porosity of ϕ = 0.047. Some of the results of the core measurements are also shown in Fig. 1. It was found that:

d) for the (low porosity) cores the value of the exponent m in equation (1b) lies between 1.65 and 1.75;

e) that S_{wc}, i.e. the critical saturation fraction of a rhyolite with porosity ϕ = 0.047, is about 0.30 (i.e. 30%).

There is an indication that the exponent m in equations (1a) and (1b) slightly increases with decreasing resistivity (see Fig. 1). but further experiments are needed to show if this trend is real. Because of experimental problems with the contact resistance, no reliable values for the exponent m' in equation (4b) could be obtained; the curves in Fig. 1 for $S_w < S_{wc}$ were drawn assuming that m' is about 4 (as found in the first experiment).

Although the experimental data are still incomplete, there is evidence from the results shown in Fig. 1 that for silicic volcanics where porosity ranges 0.05 > ϕ > 0.45, and for electrolytes within the resistivity range 1.0 Ωm > ρ_w > 18 Ω m, the following important points apply:

1) the exponent m of equation (1b) lies between 1.65 > m > 2.1 (with the higher values of m for low values of ρ_w and high values of Fa);

2) **the critical saturation (or better de-saturation) fraction lies in the rather narrow range of 0.2 > S_{wc} > 0.3.**

Implications of results for saturation fraction of the deeper 2-phase reservoir at Kamojang.

The results of these experiments can explain the observed changes in true resistivity at the boundary between the single phase condensate layer and the underlying 2-phase substratum assuming the following:

a) the average resistivity ρ_w of the hot condensates within the condensate layer, is similar to that of the electrolyte in the

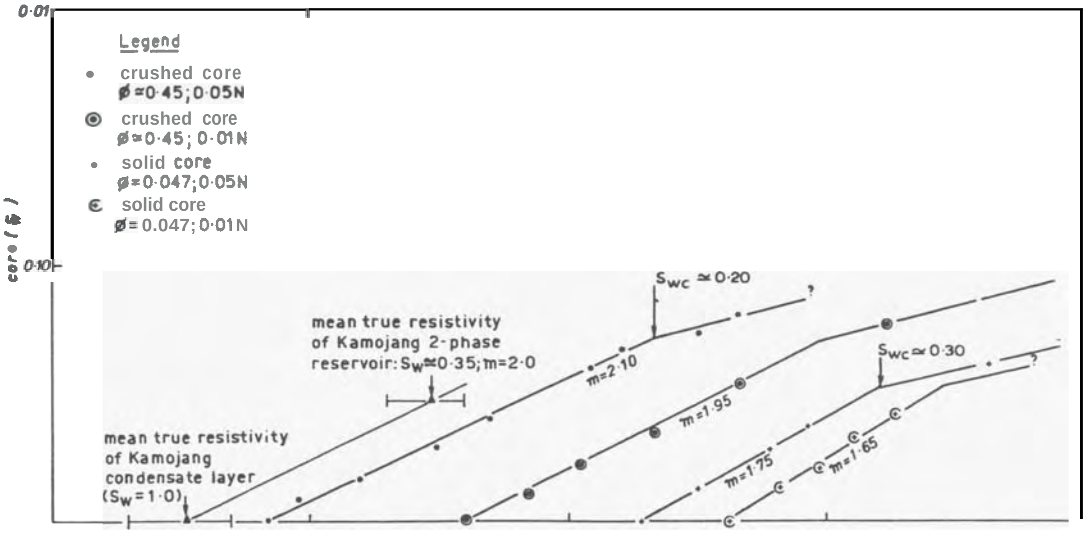

Figure 1: RESISTIVITY OF SATURATED AND PARTLY SATURATED CRUSHED ROCKS AND CORES (RHYOLITE).

2-phase reservoir (the temperature effect with depth on ρ_w within the condensate layer being partly offset by an increase in pH with depth).

β) the average matrix resistivity ρ_c, porosity ϕ, and apparent formation factor Fa are about the same in both media (there is evidence from cores to support this assumption).

Assuming further that the true resistivity of the condensate layer is about 3.5 Ω m and that of the deeper 2-phase reservoir is about 30 Ω m (as indicated by the recent sounding interpretation), these data and their error limits can be fitted into Fig. 1 using a slope of $-m = -2.0$.

It can be seen that in this case: $S_w \simeq 0.35$ (*i.e. 35 %*).

(For a slope of - 1.7 one obtains a value of $S_w \simeq 0.28$, but it is assumed here that the higher value of m holds for reasons discussed elsewhere in the paper).

It should be noted that the value obtained for S_w is independent of any assumption about the actual value of the mean porosity ϕ of the Kamojang reservoir rocks; it has only been assumed that Fa is nearly constant.

Recently M. Grant (1979) has derived a value for S_w of productive zones within the Kamojang 2-phase reservoir by developing a theory describing the transient flow of steam in the presence of immobile water and analysing the transient response of gaseous constituents in the steam; he obtained values for $S_w\phi$ of 0.09 and for S_w of 0.35 respectively. A similar value for S_w has been obtained by M. Mountford (pers. comm) using a less rigorous analysis of the enthalpies of selected production bores.

The agreement between our value of S_w and that obtained from quite different approaches by Grant and Mountford is surprising but it is probably no coincidence. One has, however, to remember that the value of S_w based on the resistivity data applies for the bulk of the reservoir down to about 800 m depth as given by the maximum depth penetration of the resistivity arrays $AB/2 \leq 1400$ m), whereas the value of &, by Grant applies to the production zone of a few wells. If further data shows that our value of S_w differs from that derived from well data (and which would be the case if the exponent m in equation 1b were less than 2), the findings could still be reconciled. By obtaining information about the critical saturation S_{wc} from resistivity data, we gain additional information why such systems might reach the actual saturation fraction of $S_w \simeq 0.35$.

If one recalls that S_{wc} for volcanics with rather low porosity is about 0.3 (i.e. 30%), and that fox values of $S_w < S_{wc}$, fluids become immobile, the mobility of any pore water in a 2-phase reservoir requires that $S_w > S_{wc}$; this is apparently true for the Kamojang reservoir.

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REFERENCES

GRANT, M.A. (1979): The Water content of the Kawah Kamojang reservoir. Geothermics (in press).

HOCHSTEIN, M.P. (1976): Geophysical exploration of the Kawah Kamojang Geothermal Field, West Java. Proceedings 2nd UN Symposium on Development and Use of Geothermal Resources 1975 (2), 1049-58. U.S. Geol. Printing Office, Washington D.C.

KELLER, G.V.; FRISCHKNECHT, F.C. (1966): Electrical methods in geophysical prospecting. Pergamon Press, Oxford, 519 pp.

LAWTON, D.C.; HOCHSTEIN, M.P. (1980): Physical properties of titanomagnetite sands. Geophysics 45 (3), 394-402.

WHITE, D.E.; MUFFLER, L.J.P.: TRUESDELL, A.H.(1971): Vapor-dominated hydrothermal systems compared with hot-water systems. Economic Geology 66 (1), 75 - 97.

WORTHINGTON, P.F. (1975): Quantitative geophysical investigations of granular aquifers Geophysical Surveys 2, 313-366,

ZHODY, A.R. (1975): Automatic interpretation of Schlumberger sounding curves, using modified Dar Zarrouk functions. U.S. Geological Survey Bulletin 1313-E, 39p.