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RESISTIVITY LOGGING OF FRACTURED BASALT

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INTRODUCTION

The electric log has been used for about half a century as a tool for studying the formations penetrated by a borehole. At early stage, comprehensive studies of sedimentary rock established the dependence of formation resistivity factor upon porosity. Archie (1942) pioneered this effort by suggesting his well-known empirical formula correlating the formation factor and porosity. Ever since, Archie's law has been a central point in interpretation methods for electrical logs.

Despite the simple empirical dependance of rock conductivity on porosity as expressed by Archie's law, there does not exist a simple theoretical explanation for this phenomenon. Mathematical modeling to prove the validity of an Archie type relationship has been carried out by Greenberg and Brace (1969), Shankland and Waff (1974) and Madden (1976). However, all models depend on simplistic geometrical assumptions of pore space distributions and the degree of realism can be disputed.

During the last decade, investigations on geothermal reservoirs have accentuated the role of fractures in reservoir physics. Various types of geophysical logs have been applied in order to distinguish between fractured and intergranular reservoirs. One of the strong candidates for that is the electric log (Towle 1962, Aguilera 1974 and 1976). The main reason for that is the fact that the exponent <m> in Archie's law seem to be 1.0 in the case of fractured rock (Brace and Orange 1968), where as a value of 2.0 seems to be valid for non-fractured rock (Brace et.al. 1965).

In this paper a simple lumped double porosity model is studied in order to estimate the effects of fractures on the resistivity-porosity relationship. Further, the results of resistivity and porosity logging in Icelandic basalt is presented, and it is shown that the distribution of porosity in these rocks are dominated by fractures.

LUMPED DOUBLE POROSITY MODEL

Consider an idealized model for fractured rock in order to estimate the effects of fractures on resistivity-porosity relations. This model is presented in figure 1 and consists of cubes representing the rock and the spacing between the parallelepipeds representing waterfilled fractures. Similar models have been presented before (Towle 1962, Aguilera 1974 and 1976, Hirakawa and Yamaguchi 1981), but the present approach is somewhat different.

The following parameters are used in the model:

- ρ_w = resistivity of water in pores and fractures
- ρ_b = resistivity of rock matrix
- ϕ_b = porosity of rock matrix (relative to matrix volume only)
- x = length of each matrix cube, fraction
- $1-x$ = width of fractures, fraction

It is convenient to introduce lumped resistances in approximating the resistivity of the model as is shown in figure 1. Thus the resistance of an unit cube is approximately given by

$$\frac{1}{R} = \frac{1}{R_1 + R_2} + \frac{1}{R_3} \qquad (1)$$

and the resistivity of the model is

$$\rho = R \qquad (2)$$

Referring to figure 1

$$R_1 = \frac{x}{x^2}\,\rho_b \qquad (3)$$

$$R_2 = \frac{1-x}{x^2}\,\rho_w \qquad (4)$$

$$R_3 = \frac{1}{1-x^2}\,\rho_w \qquad (5)$$

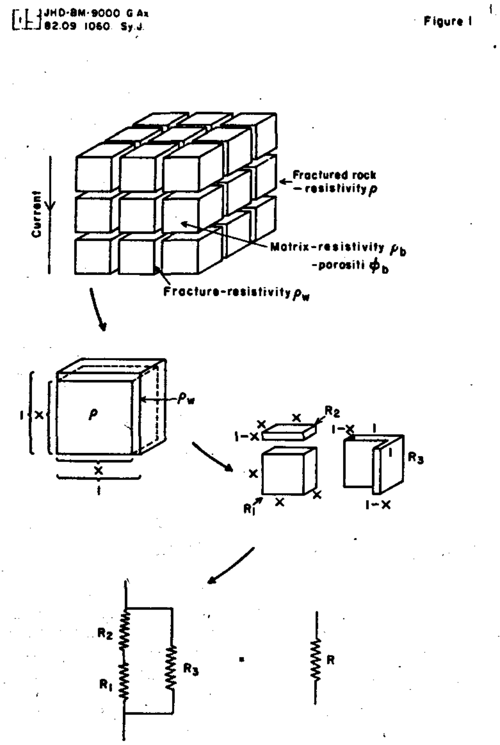

Figure 1 Schematic figure of the double porosity model and the equvalent resistivity calculated for each unit cube.

and the resistivity of the fractured rock is according to equation 1

$$\frac{1}{\rho} = \frac{1-x^2}{\rho_w} + \frac{x^2}{(1-x)\rho_w + x\rho_b} \qquad (6)$$

Introducing the fracture porosity

$$\phi_f = 1 - x^3 \qquad (7)$$

an approximation for the formation resistivity factor for the double porosity model is obtained as:

$$\frac{1}{F} = 1 - (1-\phi_f)^{2/3} + \frac{(1-\phi_f)^{2/3}}{[1-(1-\phi_f)^{1/3}] + (1-\phi_f)^{1/3}\rho_b/\rho_w} \qquad (8)$$

where

$$F = \rho/\rho_w \qquad (9)$$

Equation 8 is somewhat simpler than the one presented by Hirakawa and Yamaguchi (1981), but gives similar results.

The same approach can be used to estimate the formation factor for models with either vertical fractures only or horizontal fractures only. Omitting the details of the derivation one obtains for vertical fractures only:

$$F = \frac{1}{\phi_f + (1-\phi_f)\rho_w/\rho_b} \qquad (10)$$

and for horizontal fractures only

$$F = \phi_f + (1-\phi_f)\rho_b/\rho_w \qquad (11)$$

Equation 8 is used to estimate the formation resistivity factor for the double porosity model. Here it is assumed that

$$\rho_b = \rho_w/\phi_b^2 \qquad (12)$$

The use of an exponent of 2 is supported by the results of Brace and Orange (1968b). From their experiments with different rock samples, saturated with brine and measured at 4 kbar to close up most of the crack porosity, an exponent of 2 dependence of resistivity upon residual porosity was obtained. These results were confirmed by the simulation studies of Shankland and Waff (1975). Equation (12) has been recognized as an empirical law in the petroleum industry and is valid for normally cemented sandstone.

The relationship between the porosity and the formation factor according to equation 8 is presented in figures 2 and 3. The results for horizontal fracture only (equation 11) are presented in figure 4.

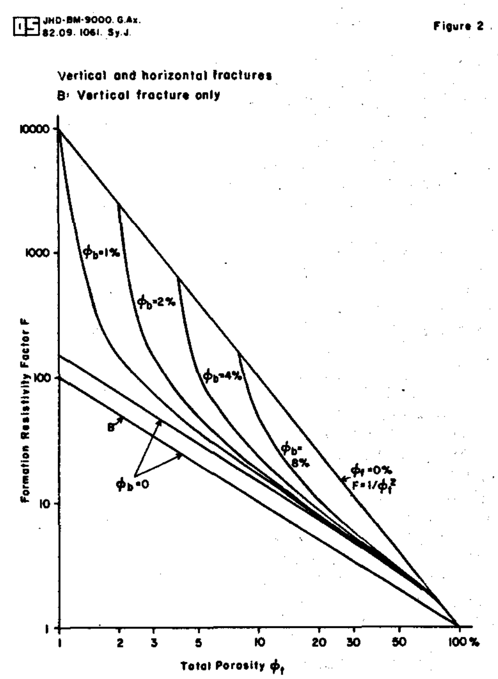

Figure 2 Relation between formation resistivity factor and total porosity as calculated from the double porosity model. Curve B represents vertical fracture only with matrix porosity equal to zero. Other curves are for cases where both vertical and horizontal fractures are present.

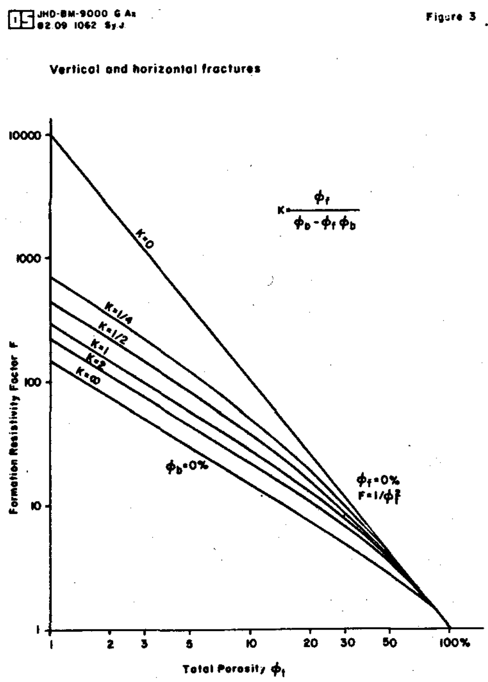

Figure 3 Relation between formation resistivity factor and total porosity for vertical and horizontal fractures, given various values of the ratio between fracture porosity and matrix porosity.

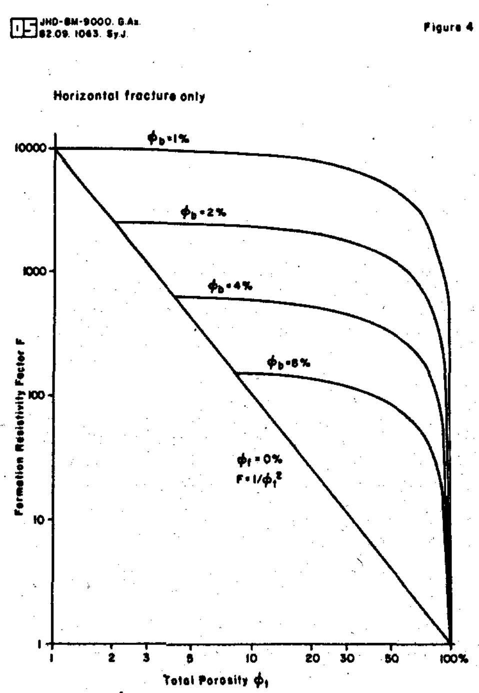

Figure 4 Relation between formation resistivity factor and total porosity for horizontal fracture only.

Equations 8, 10 and 11 can be combined with Archie's law (Archie 1942)

$$F = a/\phi_t^m \tag{13}$$

where

$$\phi_t = \phi_f + \phi_b - \phi_f\phi_b \tag{14}$$

is the total porosity. The double porosity model in the presence of vertical and horizontal fractures, when $\phi_b = 0$ and $\phi_t < 30\%$ then yields, a = 1.4 and m = 1.0. This compares favorably with the values a = 1.5 and m = 1.0 obtained by Towle (1962) for his plane model, but it is identical to the model used here. Similarly for vertical fracture only, a = 1.0 and m = 1.0 when $\phi_b = 0$. A m = 1.0 dependence upon total porosity is also seen to be valid when the ratio

$$k = \frac{\phi_f}{\phi_b - \phi_f\phi_b} \tag{15}$$

is constant and total porosity is small (figure 3), but the values for <a> increase with decreasing k-values.

These results are different from the relationships commonly used in the petroleum industry. An exponent of 1.0 is however in an agreement with the results of Brace and Orange (1968a), who observed that stressing rock samples into the dilant region of new crack formation produced an esponent of 1.0 dependence upon crack porosity.

It can be seen from the different values for <a> estimated above, for vertical and horizontal fractures, and for vertical fracture only, that resistivity-porosity relations, for fractured rock, are highly dependent on the ratio of vertical to horizontal fractures, i.e. fracture orientation. Different ratios of vertical to horizontal fractures can be modeled using the simple lumped approach used above. Space does not permit a detailed discussion, but results indicate a rapid increase in resistivity, at near constant total porosity, with decreasing importance of vertical fractures (figure 4).

The results from the above discussion can be summarized as follows.

1) Even though the present results are only a first order approximation it can be seen that the empirical relation $F = \phi^{-2}$ is not valid for fractured rock. An exponent of 1.0 is probably more correct.

2) The relationship between resistivity and porosity for fractured rock is in general not simple (figures 2, 3 and 4), but depends on the amount of matrix porosity as well as the fracture orientation.

3) Results indicate that porosity of fractured rock should not be determined form resistivity data based on a $F = a\phi^{-m}$ relation alone.

4) Assuming that the ratio of vertical to horizontal fractures is as in the model of figure 1 with total porosity and formation factor known from geophysical logging data, one can estimate roughly the relative importance of fracture- and matrix porosity by the use of the approximate model presented above.

RESISTIVITY-POROSITY RELATIONS FOR BASALT

Extensive geophysical logging has been performed in several deep (2 km) boreholes in Iceland. Among the parameters observed were resistivity (16" and 64" normal) and porosity (neutron-neutron). Examples of resistivity (formation resistivity factor)-porosity crossplots from two boreholes in basaltic environment are presented in figures 5 to 7. These figures show only few, but representative examples.

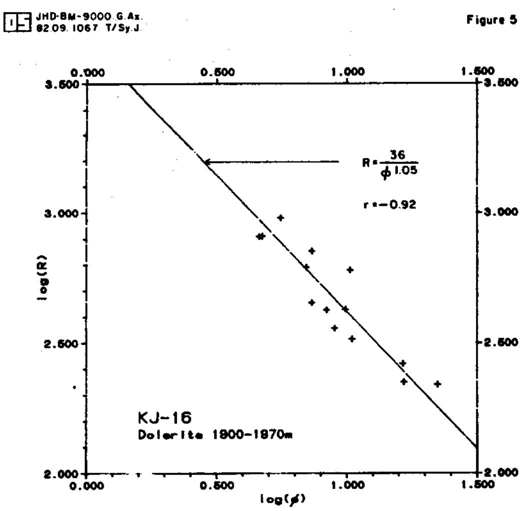

Figure 5 Resistivity - porosity cross plot for Dolerite at 1900 - 1970 m depth in well KJ-16 in the Krafla high temperature geothermal field. The best linear fit to the data points is shown along with its correlation coefficient.

Well KJ-16 is a production hole drilled inside the Krafla geothermal area (Stefánsson 1981) in the neovolcanic zone of Iceland. The IRDP-hole (Fridleifsson et.al 1982, Robinson et.al. 1982) is drilled in approximately 10 My old basalt pile in Eastern Iceland. The pore water resistivity (ρ_w) is fairly well known, as a function of depth, for the IRDP-hole, which enables the estimation of the formation resistivity factor (figures 6 and 7).

A rather good correlation between resistivity and porosity is seen for the examples in figures 5 to 7. A relationship of the form $\rho = a \rho_w \phi^{-m}$ has been fitted to these data and the results are presented in the

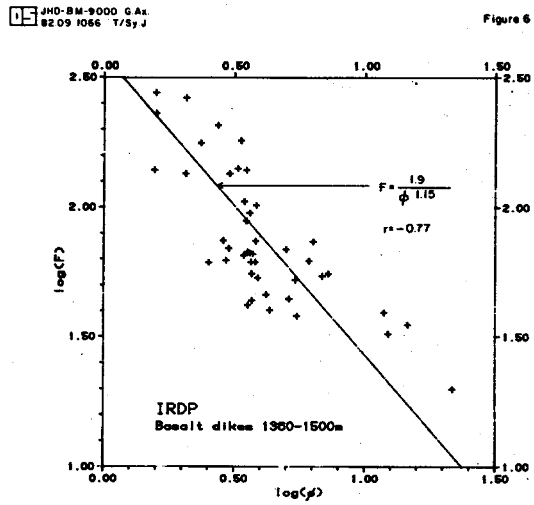

Figure 6 Formation resistivity factor - porosity cross plot for Basalt dikes in the depth interval 1360-1500 m in the IRDP hole in Eastern Iceland.

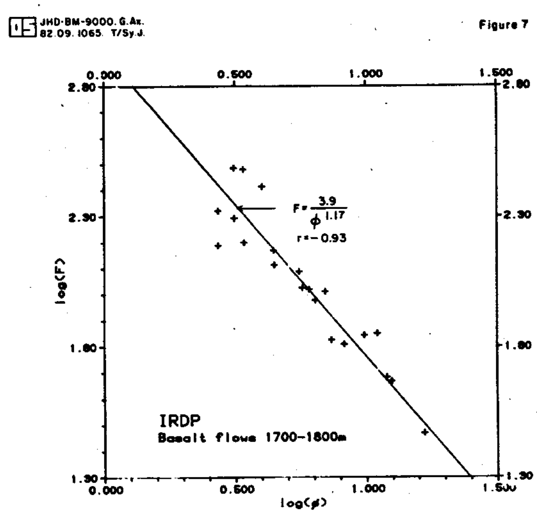

Figure 7 Formation resistivity factor - porosity cross plot for Basalt flows in the depth interval 1700-1800 m in the IRDP hole in Eastern Iceland.

figures. An equation of this form has also been fitted to data from other intervals, not presented here, and weighted average for the exponent <m> calculated for the two different areas. The results are presented in table I.

Table I

Location	Weighted Average <m>	Data based on
Krafla (0-1 My)	1.02 ± 0.07	205 m out of 2 x 1300 m
IRDP (~10 My)	1.10 ± 0.04	430 m out of 1100 m

These results are in good agreement with results for basalt from Hawaii (Keller et.al. 1974) and results from the Atlantic Ridge at 23°N (Kirkpatrick 1979).

How do we interpret an exponent <m> close to 1.0 ? This indicates, according to the double porosity model presented before and the results of Brace and Orange (1968a), that fractures constitute an important part of the porosity for the basalts studied. However, we can not determine, on the basis of the values for <m> alone, how important fractures are in the overall porosity. According to the double porosity model an exponent of 1.0 is possible, even though matrix porosity is considerable.

A more complete interpretation of formation resistivity factor-porosity cross-plots can be attempted on the basis of the double porosity model. The model can be used to estimate the relative importance of fracture- and matrix porosity when the pore water resistivity is known. We will take as examples three cross-plots from the IRDP-hole presented in figures 8 to 10. The two extremum cases ($\phi_b = 0$ and $\phi_f = 0$), for vertical and horizontal fractures, as well as one or two lines for constant k-ratios are superimposed on these cross-plots. We see from the figures that these data can be interpreted on the basis of the double porosity model. An interpretation of that kind is of course approximate, requires an exact knowledge of the value for and is limited by the underlying assumption of fracture orientation.

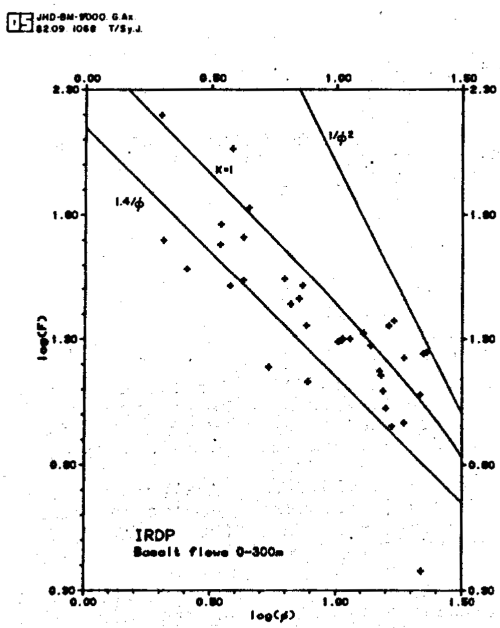

Figure 8 Relation between formation resistivity factor and total porosity for Basalt flows in the depth interval 0-300 m in the IRDP hole in Eastern Iceland. Superimposed are lines for the two extremum cases $\phi_b = 0$ and $\phi_f = 0$ and one line for constant ratio between fracture porosity and matrix porosity.

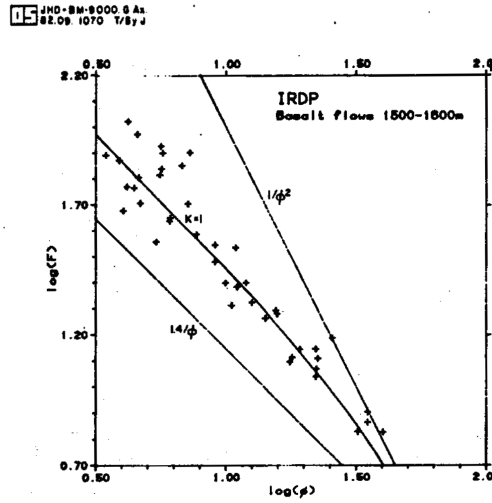

Figure 9 Relation between formation resistivity factor and total porosity for Basalt flows in the depth interval 1500-1600 m in the IRDP hole in Eastern Iceland. Superimposed are lines for the two extremum cases $\phi_b = 0$ and $\phi_f = 0$ along with a line for constant ratio between fracture porosity and matrix porosity.

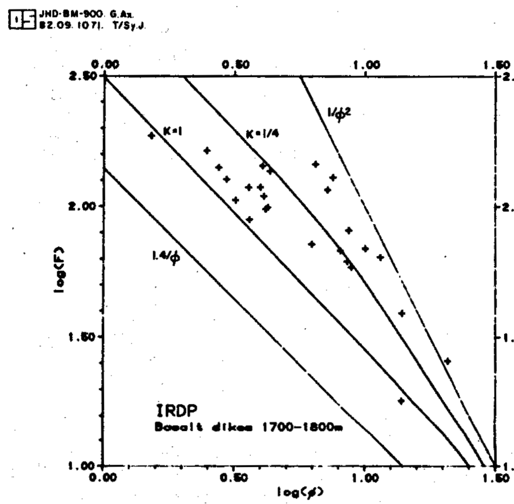

Figure 10 Relation between formation resistivity factor and total porosity for Basalt dikes in the depth interval 1700 - 1800 m in the IRDP hole in Eastern Iceland. Superimposed are lines for the two extremum cases $\phi_b = 0$ and $\phi_f = 0$ along with lines for constant ratio between fracture porosity and matrix porosity.

Using figure 3 we can estimate roughly the ratio of fracture- to matrix porosity. For the cases from the IRDP-hole presented in figures 8 to 10 the following results are obtained (table II):

Table II

Interval	ϕ_f / ϕ_t
0-300 m Basalt flows	≈0.7
1500-1600 m Basalt flows	≈0.5
1700-1800 m Basalt dikes	≈0.2-0.3

The apparent decrease in fracture porosity with depth is noteworthy, but the underlying assumptions mentioned above should be kept in mind. A decrease in fracture porosity could be the result of increasing pressure with depth closing up some fractures. This effect could on the other hand also result from changes in fracture orientation with depth.

To conclude this discussion we present one example for a non-basaltic unit in figure 11, where formation resistivity factor - porosity crossplot for a diorite (55% SiO) unit from the IRDP-hole is shown. Here we see a relationship which is quite different from the relationships for the basalt presented above. Interpreting the data in figure 11 according to the double porosity model we find that fracture porosity should be insignificant in this diorite unit.

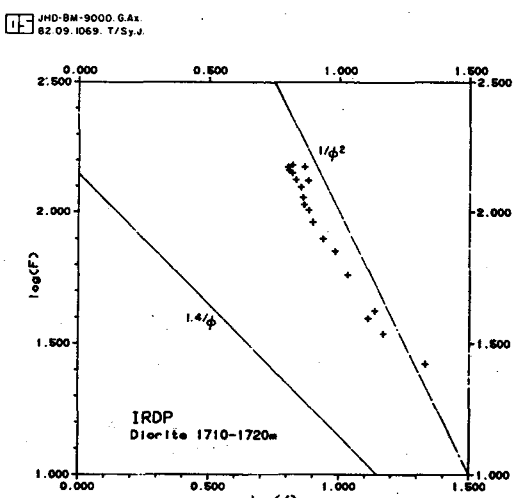

Figure 11 Relation between formation resistivity factor and total porosity for 10 m thick Diorite formation at 1710 m depth in the IRDP hole in Eastern Iceland. Superimposed are lines for the two extremum cases $\phi_b = 0$ and $\phi_f = 0$. The data points fall close to and parallel with the line $\phi_f = 0$ indicating that fracture porosity is negligible.

CONCLUSION

A lumped double porosity model has been studied in order to estimate the effect of fractures on resistivity - porosity relations. It is found that the relationship between resistivity and porosity for fractured rock is in general not simple and depends both on the amount of matrix porosity as well as the fracture orientation. However, when fractures dominate over matrix porosity the exponent <m> is close to 1.0.

Resistivity-porosity relations have been determined for large amount of basaltic formations in Iceland. An exponent close to 1.0 is found in all cases investigated. This is interpreted as fractures constitute a considerable part of the porosity of the basalts. In the IRDP-hole in Eastern Iceland it is found that the ratio of fracture porosity to total porosity decreases with depth.

In contrast to the exponent of 1.0 found for basaltic formations in Iceland, many interbedded formations in the basaltic pile reveal an exponent of approximately 2.0. This is interpreted as matrix porosity dominates fracture porosity in these cases.

The study of resistivity-porosity relationship presented demonstrates that common geophysical logs can distinguish between fractured and porous reservoirs.

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