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FRACTURE CHARACTERIZATION OF THE GEOTHERMAL RESERVOIR INFERRED FROM PRESSURE TRANSIENT DATA

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ABSTRACT

Pressure transient tests were carried out to evaluate hydraulic properties of fractured reservoirs in the Hohi geothermal field in Japan, where a crosswell seismic tomography has recently conducted to identify a fracture zone.
These tests were composed of multi-rate water injection test and air pressure pulse injection test.
Pressure data were analyzed using classical line-source solution and the reservoir model made of two regions, i.e. a high permeability zone near the well for a large negative skin and a low permeability beyond the high permeability zone.
These results imply that not all of the fractures intercepted by individual wells extend very far (i.e. beyond about 20 meters) into the formation. These results are also consistent with those obtained from circulation loss data and seismic tomography data.
As compared to conventional injection test, pulse tests were available to determine near wellbore formation properties.

INTRODUCTION

Geothermal reservoirs are usually found in fractured rock formations. The fractures serve as conduits for geothermal fluids, and the relatively low permeability country rock provides the reservoir storage capacity. Characterization of the fracture and matrix hydraulic properties is required for predicting the response of the reservoir to fluid production and injection. While matrix properties (porosity, compressibility, permeability) can be determined from laboratory tests on cores recovered during drilling, the corresponding fracture properties can only be evaluated from insitu studies.

However, mapping the fracture distribution within the reservoir comprises a formidable task, since effective exploration techniques for fractured reservoirs do not exist, and in the early stages of field development only a few well are present. Therefore, fracture mapping based only on drilling results will be very crude.

New exploration techniques such as high resolution reflection seismic survey, VSP, and seismic tomography have been recently developed in order to make them applicable to fractured geothermal reservoirs. Since a fractured zone will usually be characterized by relatively low seismic velocity anomalies or discontinuity of reflection events etc., these anomalous zones may represent a potential drilling target.

The difficulty is that the presence of a fracture system is not the only possible cause for local seismic anomalies. Moreover, even if a fracture system is present, it may not represent a productive zone owing either to isolation from the flow pattern or to plugging by minerals produced by fluid-rock chemical interactions. A need exists for a procedure to distinguish those seismic characteristics which represent permeable zones conducting geothermal fluids from other, false indicators.

Perhaps the most important technique for characterizing the hydraulic properties of a fractured geothermal system consists of performing (and interpreting) pressure transient tests.
Pressure transient tests are an established part of reservoir/aquifer characterization in petroleum and groundwater engineering. The use of pressure transient tests in geothermal reservoir engineering has been the subject of active research in the last two decades. With the development of new and innovative measurement and interpretation

techniques, pressure transient tests are beginning to provide valuable insights into the hydraulic properties of geothermal reservoirs. In this paper, hydraulic properties of the fracture zone integrating pressure transient data with seismic tomography data and other well data are presented.

PRESSURE TRANSIENT TESTS

1) Well conditions and measurement

Pressure transient tests were carried out in wells YT-1, YT-2 in which seismic tomography was conducted.The wellheads for two wells are located about 300 meters apart, and are at nearly the same elevation. YT-1 and YT-2 were both drilled to a depth of 1700 meters; the open interval in both of these wells extends from 1500 meters to 1700 meters. Lithology from a depth of 1300 meters to 1700 meters is composed of andesitic tuff breccia and lava.

Both multi-rate water injection tests and air pressure pulse injection test were carried out. During these injection tests, downhole pressure was monitored in wells YT-1 and YT-2 using capillary-tube type pressure gauges. The main purpose to conduct the air pulse test was to study its utility as a substitute for the conventional water injection test at geothermal fields where it is hard to obtain much injection water.

① Multi-water-injection test
Cold water was injected into well YT-2 for 168 hours. The injection rate history consists of three steps(1st injection rate: 96 l/min for 24 hours, 2nd: 205 l/min for 48 hours, 3rd: 303 l/min for 96 hours). Fall-off pressure after injection was observed for 315 hours. The recorded pressure and injection-rate history of well YT-2 and pressure response of well YT-1 are shown in Figure 1.

② Air pressure pulse test
Pulse tests were conducted after the above fall-off test. Seven pulse tests were carried out with triangular air pressure variation at the wellhead of YT-2 continuously created by a air-compressor (Black, 1986; Noy, 1988). The increase or the decrease in wellhead pressure results in a lowering or a rising of the water table in the well and inflow or outflow of a volume of water into or from the formation. Pulse tests 1 and 3 each consisted of 4 cycles (i.e., 4 cycles of increase/decrease in the wellhead pressure). All other pulse tests consisted of a single cycle. During the pulse tests, the water level in YT-2 was monitored using an echometer. These water level data are displayed in Figure 2. The maximum pressure and the periods of a triangular air pulse were 40 bars and 20 hours, 12 hours, 6 hours respectively.

Pressure history of well YT-2 during pulse test 1 are shown in Figure 3.

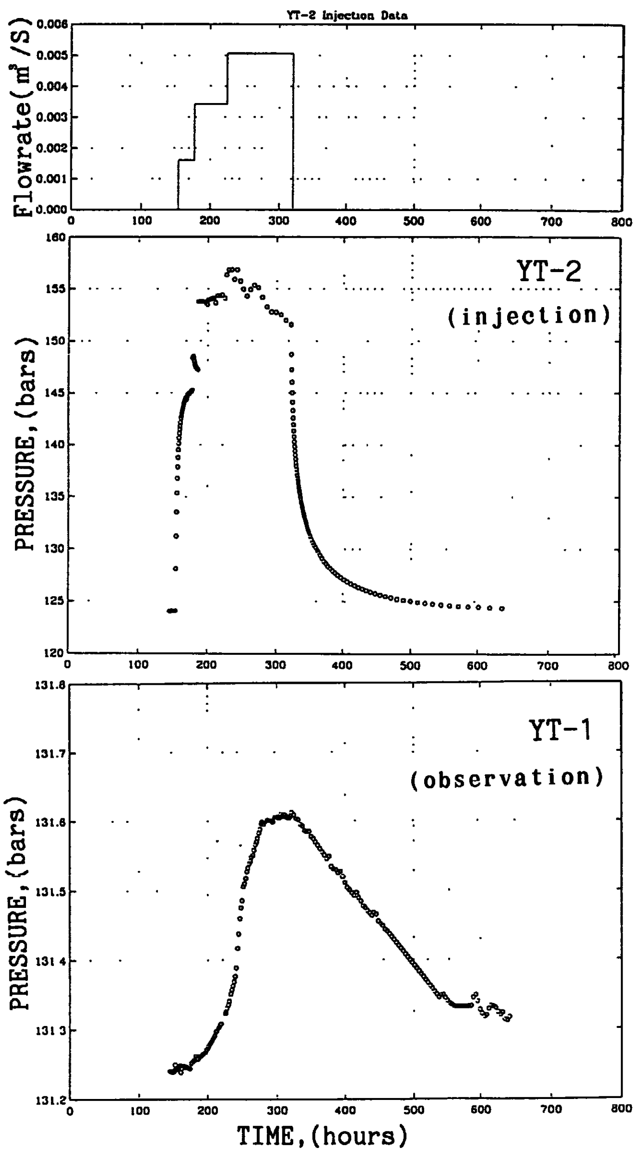

Figure 1. Injection rate (top panel) and pressure record (middle & bottom panels) for the multi-rate injection test of well YT-2 and YT-1 (YT-2; injection well, YT-1; observation well)

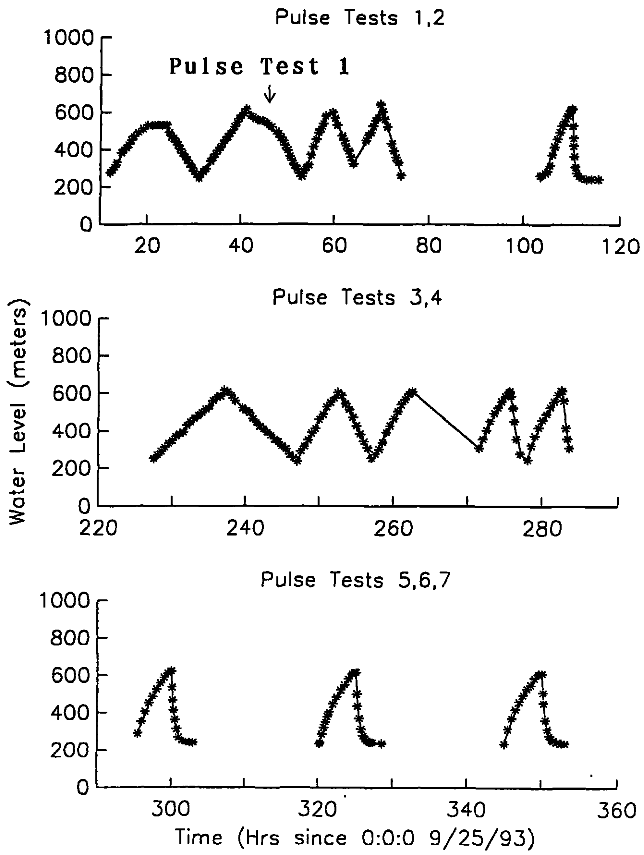

Figure 2. **Water levels (depth of water table below the wellhead) recorded by an echometer in Well YT-2 during pulse tests**

2) Data Analysis

A pressure interference response was seen in YT-1 during multi-rate injection into well YT-2, but such response was obscure during the pulse tests. Pressure data were analyzed using the classical line-source solution and the composite reservoir model as a large negative skin was indicated by the conventional graphical analysis.
The composite reservoir model assumes that the reservoir is made up of two regions; a high permeability zone adjoining the wellbore and a low permeability zone beyond the high permeability zone. The near wellbore high permeability zone largely determines the early-time pressure response; the late time pressure response is governed by the at-large low permeability zone.
The formation parameters inferred from line-source solution analyses are listed in Table 1. The data analysis was performed by nonlinear least squares estimation of reservoir model parameter for a variety of mathematical models. The match between the computed and measured pressures is shown in Figures 4a(well YT-1) and 4b(well YT-2).

Permeability-thickness (kh) and storage (ϕch) parameters inferred from well YT-2 fall-off data(multi-rate injection test) are consistent with those obtained from pressure interference observed in YT-1(multi-rate injection test). These results indicate that both YT-1 and YT-2 are completed in a low-permeability and low storage formation. The YT-2 fall-off data(multi-rate injection test)also indicate a large negative skin;this implies that the near wellbore region had higher permeability than the formation at large.

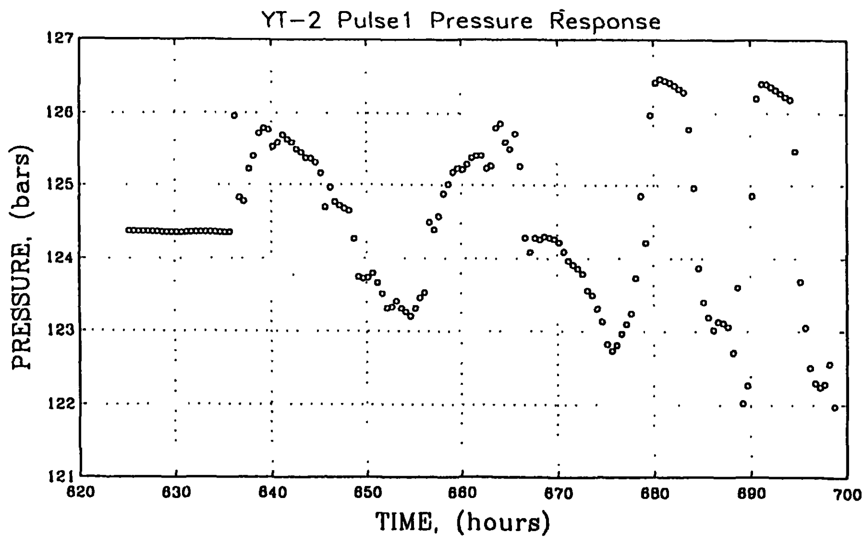

Figure 3. **Pressure record of well YT-2 during "pulse test 1"**

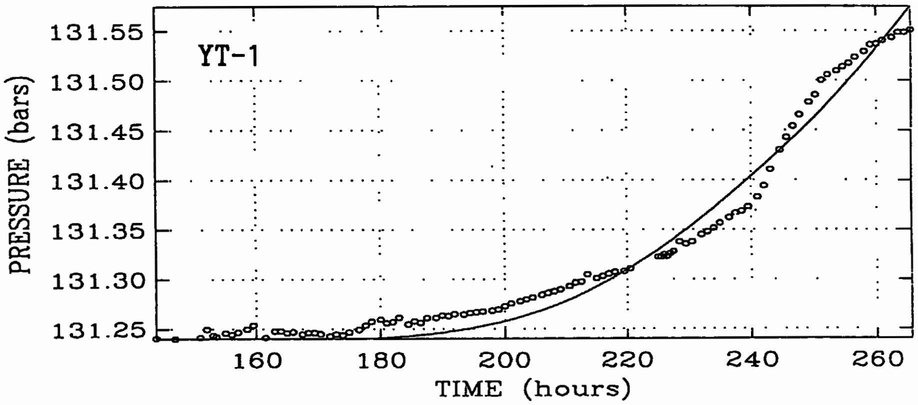

Figure 4a. Comparison of measured (o) and computed (—) pressure response of well YT-1 to injection into YT-2

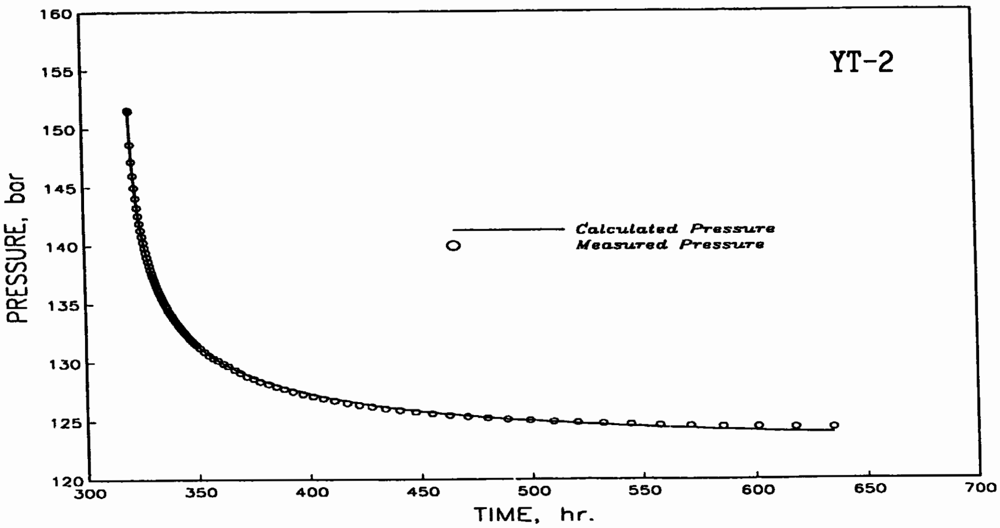

Figure 4b. Comparison of measured (o) and computed (—) fall-off pressures in well YT-2 for the multi-rate injection test.

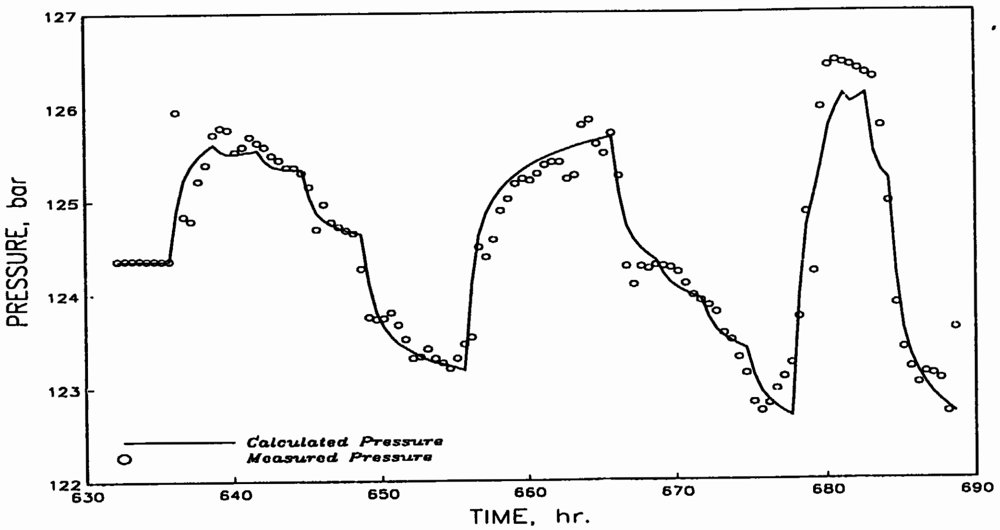

Figure 5. Comparison between measured (o) and computed (—) pressures for the first 3 cycles of pulse test 1 of YT-2

The model parameters inferred from the composite reservoir model are as follows:

Initial pressure, $Pi = 122.1$ bars

Near Well Region ($r < 19.8 meters$) :

Permeability-thickness, $(kh)_1 = 1.077$ darcy-meter

Storage coefficient, $(\phi ch)_1 = 2.28 \times 10^{-8} m/Pa$

Skin, $s = -0.11$

Wellbore storage $= 2.39 \times 10^{-5} m^3/Pa$

Far Field ($r > 19.8 meters$) :

Permeability-thickness, $(kh)_2 = 0.119$ darcy-meter

Storage coefficient, $(\phi ch)_2 = 1.24 \times 10^{-8} m/Pa$

The far field kh and ϕch values obtained from the composite model are essentially the same as those given by the line-source model. The kh value for the near well region is about an order of magnitude larger than the corresponding far-field value. The storage coefficient for near well region is about a factor of two larger than that for the far field zone. These results imply that not all of the fractures intercepted by well YT-2 extend very far (i.e., beyond about 20 meters) into the formation. The storage results imply that about one-half of the fracture volume encountered by N3-YT-2 does not continue beyond about 20 meters into the formation. Judging from the relative magnitude of kh values for the two regions, it would also appear that the continuous fractures(i.e., fractures that extend beyond 20 meters) have a smaller aperture than the discontinuous fractures.
The formation parameters derived from analyses of pulse tests(Table 1) appear to be somewhat different from those obtained from the multi-rate test.
The match between measured and computed pressures is shown in Figure 5.

Permeability-thickness(kh) and some storage (ϕch) parameters are consistent to an order of magnitude with those obtained from multi-rate injection test. The differences between the two sets of parameters arise primarily from the differences in duration of the two tests. As compared to conventional injection test, pulse tests were available to determine near wellbore formation properties in geothermal fields that do not receive much injection water.

DISCUSSION and CONCLUSIONS

To obtain insight into the character of the fractured reservoir intercepted by wells YT-1, and YT-2, pressure data were integrated with other well data (Schlumberger's FMS/FMI logs, well geology, drilling records, seismic tomograghy, VSP etc).
The fracture intervals inferred from an interpretation of FMS/FMI logs are compared with circulation loss data. All of the circulation loss zones for wells YT-1 and YT-2 coincide with fracture intervals as obtained from FMS/FMI logs; the reverse is, however, not true.
The representative fractures image of FMI logs are shown in Figure 6.

Table 1. Formation and wellbore parameters inferred from anayses of multi-rate injection and pulse tests

Reservoir Parameter	Multi-Rate Injection Test		Pulse Test #1 (YT-2)			Pulse Test #3 (YT-2)		
	YT-2 (Fall-off)	YT-1 (Interference)	3 Cycles	First Cycle (Complete)	First Cycle (Fall-off)	2.5 Cycles	First Cycle (Complete)	First-Cycle (Fall-off)
kh (darcy-meter)	0.114	0.134	0.180	0.117	0.133	0.244	0.291	0.294
ϕch (m/Pa)	1.85 10^{-8}	2.63 10^{-8}	1.37 10^{-7}	2.31 10^{-7}	2.12 10^{-7}	2.73 10^{-8}	2.66 10^{-8}	0.612 10^{-8}
skin (s)	−4.61	NA	−2.81	−3.27	−3.09	−3.21	−3.10	−3.90
Wellbore Storage (m^3/Pa)	3.06 10^{-5}	NA	4.63 10^{-7}	3.15 10^{-9}	1.73 10^{-8}	7.83 10^{-7}	4.38 10^{-6}	3.23 10^{-6}

NA = Not applicable

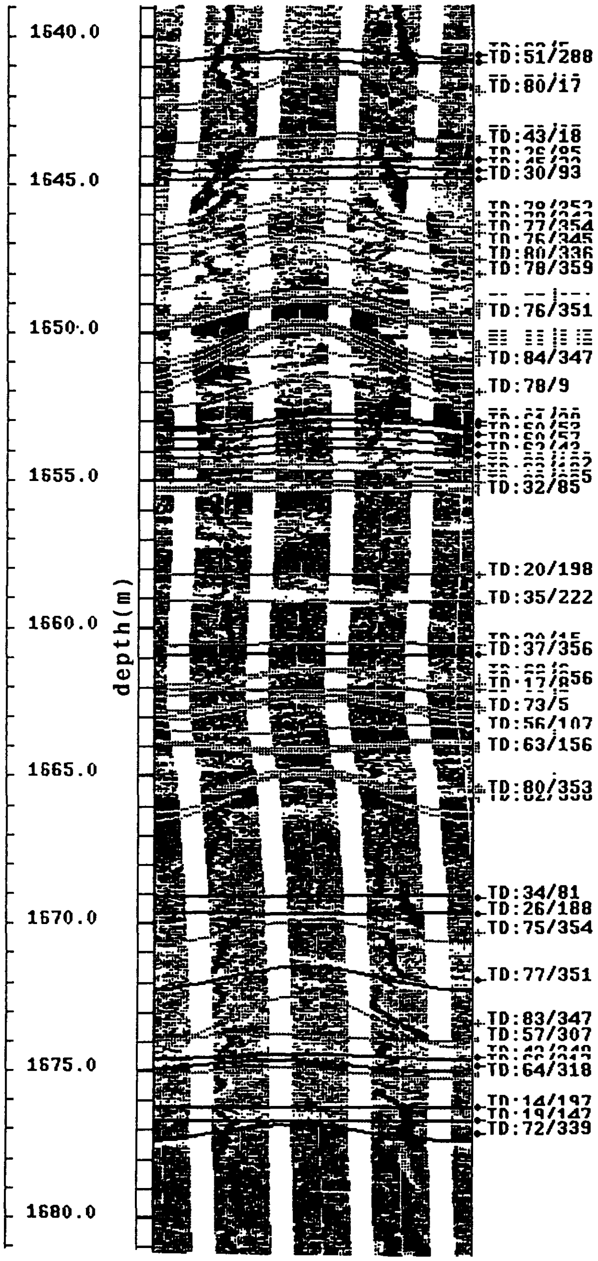

Figure 6. Schlumberger's FMI log image from 1640m to a depth of 1680m of well YT-2. sine wave; fracture, TD; true dip (magnitude/azimuth)

Well YT-2 did not encounter any circulation loss zones for hundreds of meters above the loss zone at 1646 meters; it was drilled with continuous small circulation loss from 1646 meters to total depth (1700 meters). Thus the relatively permeable interval in well YT-2 is at least 54 meters thick. Well YT-1 did not encounter any circulation loss zones above 1638 meters. Relatively large circulation loss zones were encountered while drilling YT-1 from 1638 to 1648 meters. Several additional circulation loss zones were seen from 1659 to 1700 meters. Thus, it would appear that the permeable zone in YT-1 extends from 1638 meters to total well depth. Well DY-6 located near YT-1 encountered a relatively large circulation loss zone at 1639 meters; small additional circulation loss zones reached up to 1764 meters (NEDO, 1984). All three wells show a major circulation loss at about 1639 meters. Based on DY-6 data, it would appear that this relatively permeable zone is about 125 meters in thickness.

The top of the permeable interval (about 1639 meters) is well constrained by data from three wells; the bottom of the permeable interval (~1764 meters) is based on data from a single well DY-6. The circulation loss data imply that the permeable interval from 1639 to 1764 meters is isolated by essentially impermeable rocks on both the top and the bottom. With a kh of 0.119 darcy-meters inferred from the composite model for the formation at large and formation thickness of about 125 meters, the formation permeability is estimated to be around 1 millidarcy.

Fracture zones were not also clearly detected from the data of seismic tomography and VSP conducted in the well YT-1 and YT-2.

In summary, we conclude that the pressure transient data in concert with the circulation loss data imply that some of the fractures intersected by individual wells may not extend beyond about 20 meters into the formation, and the continuous fractures (i.e., fractures that extend beyond 20 meters) have a smaller aperture than the discontinuous fractures.

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