ANALYSIS OF GEOTHERMAL WELL TEST DATA FROM THE ASAL RIFT AREA, REPUBLIC OF DJIBOUTI

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ABSTRACT

The Asal area has been described as a segment of the world oceanic rift system by earlier investigators. A total of six deep wells have been drilled in the area, the first two in 1975 and the last four in 1987 and 1988. Well Asal 2 was damaged, wells Asal 4 and Asal 5 were impermeable although very hot, but wells Asal 1, 3 and 6 have produced extremely saline fluids from 1000-1300 m depth where the aquifer temperature is about 260°C. Well test data from wells Asal 3, 4 and 6, including injection test data, draw-down test data, pressure build-up data and pressure interference data have been analyzed in order to estimate the reservoir properties of the Asal geothermal system. The permeability thickness of the deep geothermal reservoir is estimated to be about 4-8 Dm. During long-term exploitation a large pressure draw-down is observed in the reservoir. Wells Asal 3 and Asal 6 produce highly saline (120 g/l) reservoir fluid and the scaling of galena at high pressure reduces the discharge rate. Extensive exploration and field tests need to be performed to accurately estimate the actual size and capacity of the Asal reservoir. Laboratory studies should be conducted in order to find chemical inhibitors that may solve the scaling problem. If the outcome of these tests is positive, new production wells should be drilled. It is recommended that the suitability of a 130°C resource found between 400 and 600 m depth in the Asal area be studied for binary power production.

1. INTRODUCTION

The Republic of Djibouti (23,000 km^2) is located in East Africa where three major extensional structures, the Red Sea, the East African rifts and the Gulf of Aden join forming the Afar Depression (Barberi and al. 1975). This particular area is characterized by the presence of geothermal resources revealed by numerous hot springs found in different parts of the country. The most active structure is the Asal Rift which is the westward prolongation of the Gulf of Aden-Gulf of Tadjoura Ridge.

Geothermal exploration in the Republic of Djibouti was initiated by drilling of two wells in the rift of Asal in 1975 (BRGM, 1980a) which recognized a deep reservoir at 1000 m depth with high salinity and 260°C. Additional geothermal exploration in the Republic of Djibouti consisted of the drilling of two exploratory wells in the Hanlé plain, followed by four wells in the Asal Rift (Aquater, 1989).

The project started in December 1986 with the drilling of well Hanlé 1 in the Hanlé plain (Figure 1). On the basis of the low temperatures recorded in wells Hanlé 1 and 2 (72°C at 1400 m and 123°C at 2017m, respectively), and considering that high-temperature fluids were known to exist in the Asal Rift (BRGM, 1980b), four wells were drilled in the Asal area.

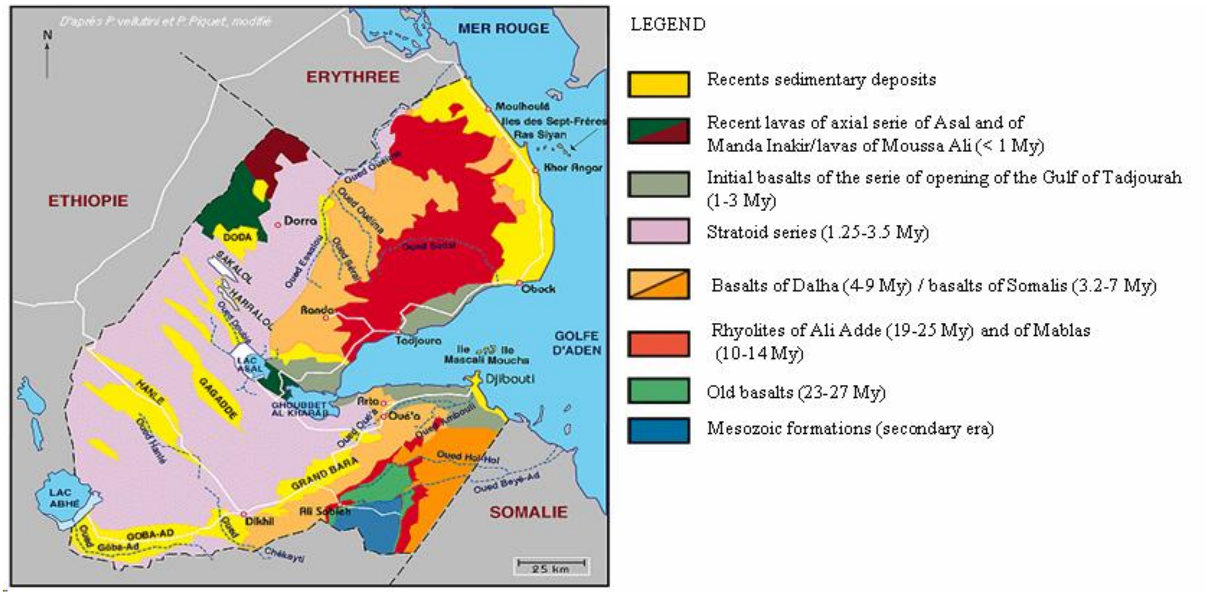

FIGURE 1: Geological map of the Republic of Djibouti

The exploration geothermal programmes of the Asal area, included field studies and exploration drilling between 1970 and 1990, revealed the high salinity, deep Asal geothermal reservoir and other potential geothermal areas. However, all these investigations did not allowed yet lead to any exploitation of the geothermal energy.

This report reviews available geological information on the Asal geothermal area and information on the geothermal wells in the area. The main purpose of the report was the analysis of well test data from wells in the area, including injection test data, draw-down test data, pressure build-up data and pressure interference data in order to estimate the reservoir properties of the Asal geothermal system. Finally, some recommendations concerning future development of the Asal geothermal resources are presented.

2. THE ASAL GEOTHERMAL FIELD

2.1 Geography

The Asal geothermal system is located on the isthmus between Lake Asal and Ghoubet al Kharab gulf (Figure 2) at a distance of about 120 km from Djibouti City. Altitudes range from -151 m at Lake Asal to +300 m at the highest point of the Rift valley floor. The area is bounded by the high plateaus of Dalha to the north (above 1000 m elevation) and by 400-700 m high plateaus to the south, which separate Asal from the Gaggade and Hanle sedimentary plains (Figure 1).

The region is arid desert, with an average rainfall of 79 mm per year. Hydrogeological studies of the region show a general groundwater flow toward Lake Asal, which is the lowest point of the area, and is occupied by a salt lake saturated in sodium chloride and calcium sulphates. The area is controlled by tectonic faults, still active.

2.2 Geology

The Asal Rift is tectonically the most active structure in the zone of crustal divergence in Afar (Figure 2). The Asal area constitutes a typical oceanic type rift valley, with a highly developed graben structure displaying axial volcanism. The Asal series are relatively complex in structure, because of different series of active volcanism in recent Quaternary times, each with very different characteristics depending on the sites of appearance. Generally, the Asal series are composed of porphyritic basalt formations and hyaloclastites.

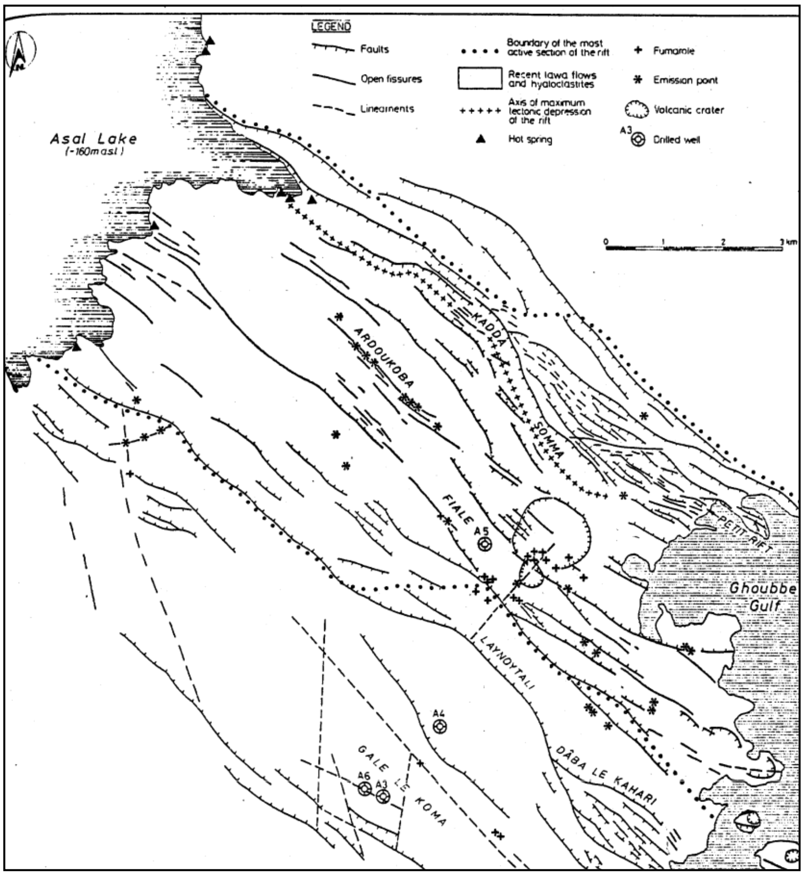

FIGURE 2: Structural map of the Asal area

The initial basalt series are an ensemble of piles of fine flows with phenocrystal of plagio- clases and olivine. The stratoid series are essentially constituted by basalts, where the top series is marked by Pleistocene clays. The basalt series of Dalha are characterized by sedimentary layers in- between the basalt flows.

Three main geological formations are known in the region and intersected by the wells. These are the Asal series (recent basalts on the geological map in Figure 1) with volcanism dating from the last 800,000 years (volcanism of the external margins of Asal, central volcanism and axial volcanism); the initial basalts series, or the stratoid basalts series, covering the period from 3.4 to 1 My; and the Dalha basalts series, dating between 9 and 3.4 My.

3. WELL INFORMATION

3.1 Wells locations

The three boreholes Asal 1, 3 and 6 are located in the southern zone of the Asal rift, inside the half circle of hyaloclastite known as Gale le Koma. Wells Asal 1 and 3 are only 30 m apart; so in the following discussions only data of well Asal 3 will be considered. The distance between Asal 3 and 6 is approximately 300 m, along a line striking NW-SE. The two sites, Asal, 1/3 and 6 are located near a NW-SE fracture. Well Asal 2 is located 800 m southeast of the Asal 3 site. Asal 4 is located about 2 km north-northeast of the site of Asal 3 and 6, close to a NW-SE fracture. It is located on the same tectonic segment as the site of Asal 3 and 6. A major tectonic step-out is located 3 km further to the northeast; and well Asal 5 is located further away in the same direction at the axis of the rift. One can also note that well Asal 5 is located nearly 500 m from a major active fault.

3.2 Main aquifers

Geological series distinguished from drilling samples are essentially based on the lithological characteristics and on the mineralogy. According to observations at the surface, the stratoide series and the more ancient Dalha basalts are separated by a layer of compact and grey clay. This clay layer was identified in the cuttings and corresponds to a quiet period with regard to tectonics and volcanism.

The stratigraphy encountered in the wells confirms what was expected from surface studies except in well Asal 5 where it was difficult to distinguish between the Asal series and Dalha series. All the feed zones encountered during drilling of the 6 wells are summarised in Table 1.

TABLE 1: Stratigraphy of Asal wells

Wells	**Coordinates**			**Depth (m)**	**Feed zones (m)**	**Aquifer formations**
	x (m)	**y (m)**	**z (m a.s.l.)**			
Asal 1	224781.47	1277342.33	191.026	1146	See Asal 3	
Asal 2	225429.28	1276814.12	187.63	1554	250-500	Stratoid basalt series
Asal 3	224800.36	1277342.35	192.665	1316	240-250 400-460 540-550 1050-1075 1225-1250 1275-1316	Contact hyaloclastite/scoria A.S. Rhyolite of stratoid series Trachyte of stratoid series Dalha basalts series
Asal 4	225740.92	1278432.56	201.607	2013	250-420	Basalts, and contact basalt-hyaloclastite of Asal Series Basalts, trachytes and alluvium of Asal Series
Asal 5	226303	1281353	125	2105	200-500	
Asal 6	224525.25	1277427.46	183.223	1761	220-270 400-600 1000-1300	Scoria of stratoid series Rhyolite/trachyte stratoid series Dalha basalts series

3.3 Analysis of well Asal 3

Well Asal 3 was drilled in 1987 to a total depth of 1316 m. The well cased with 9-5/8" to 1016 m and it is open hol between 1016 and 1316 m.

For all the tests in transient regime the measurements of pressure were made at 1075 m depth, thus near the upper permeable zones of the deep reservoir in well Asal 3. The data correspond essentially to the phase of investigation ISERST / AQUATER which took place between 1987 and 1988.

The curves of four drawdown tests are presented on a semilogarithmic graph in Figure 3. Notice that the effect of the capacity of the borehole is almost unimportant or seem to be over at very short period, less than ten minutes and there is no effect of fractures seen.

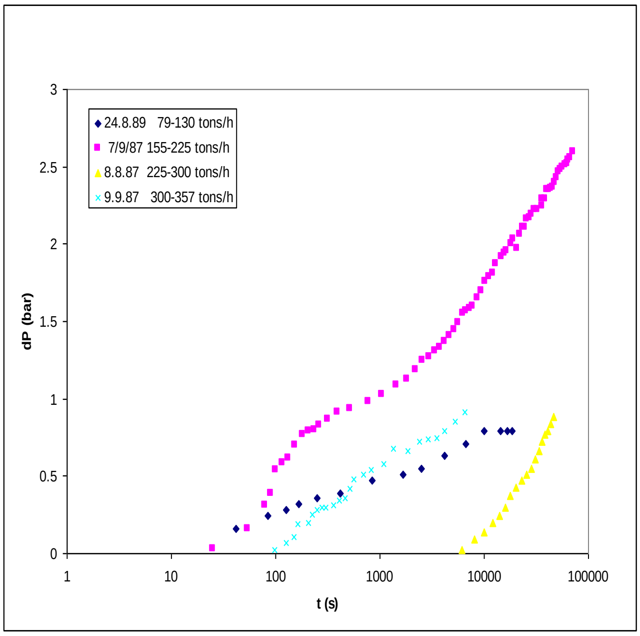

FIGURE 3: Semilog graph of drawdown tests at different times

Short wellbore storage indicates a good hydrodynamics characteristic of the reservoir near the wellbore (Grant et al 1982; Horne, 1995).

Considering the high salinity (120 g/l) and the temperature (263°C) of the fluid in the reservoir, the following values for the dynamic viscosity and the density of fluid were selected for the interpretations:
$\mu = 1.4\ 10^{-4}$ Pa s $\rho = 890$ kg/m^3

For the type curve match, the model "Dimensionless pressure for a single well in an infinite system, wellbore storage and skin included" (Argawal et al. 1970) was used. The compressibility of basalt rock $C_r = 2\ 10^{-11}$ Pa^{-1}. The results of interpretation of the drawdown tests from the semilog method, the type curve match and for multiflow rates (shown in Figure 4) are presented in Table 2 (Daher, 2005).

TABLE 2: Results from drawdown tests

			Semilog		**Match method**		
Date	**q (tons/h)**	**Δq (tons/h)**	**m (Pa)**	**kh (Dm)**	$\begin{pmatrix} t_D;P_D \\ t(s);\Delta P(Pa) \end{pmatrix}$	**skin**	**kh (Dm)**
24.8.87		51	0.29E5	14	$\begin{pmatrix} 1E6;10 \\ 2000;2.6E5 \end{pmatrix}$	-5	13.6
24.8.87	Multiple		18.05 (bar/(tons/s))	16			
7.9.87	155-225	70	0.976E5	5.75	$\begin{pmatrix} 1E7;10 \\ 72000;7E5 \end{pmatrix}$	-5	7
8.9.87	225-300	75	1.43E5	4.2	$\begin{pmatrix} 10;10 \\ 5000;12E5 \end{pmatrix}$	-5	4.3
9.9.87	300-357	57	0.33E5	14	$\begin{pmatrix} 1E6;1 \\ 600;0.25E5 \end{pmatrix}$	-5	15.9

From these results, we distinguish two ranges for the transmissivity values i.e. 14-16 Dm at 50-57 tons/h and 4-6 Dm for 70-75 tons/h. This involves:

- The heterogeneity of the reservoir,
- In the vicinity of the well, there is a zone more permeable (14-16 Dm) tapped by the flow rate 50-57 tons/h and when the flow rate increases to 70-75 tons/h, the influence zone is larger and reaches some limits less permeable (4-6 Dm) around the well.

The skin factor is negative (-5). Skin is an additional pressure change to the normal pressure change in the near vicinity of the well due to production. The negative factor obtained indicates that the well is in good communication with the reservoir.

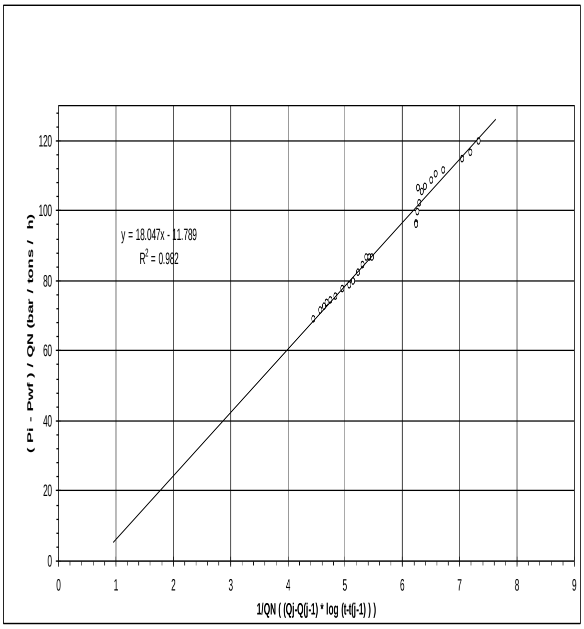

FIGURE 4: Well Asal 3 multirates drawdown test

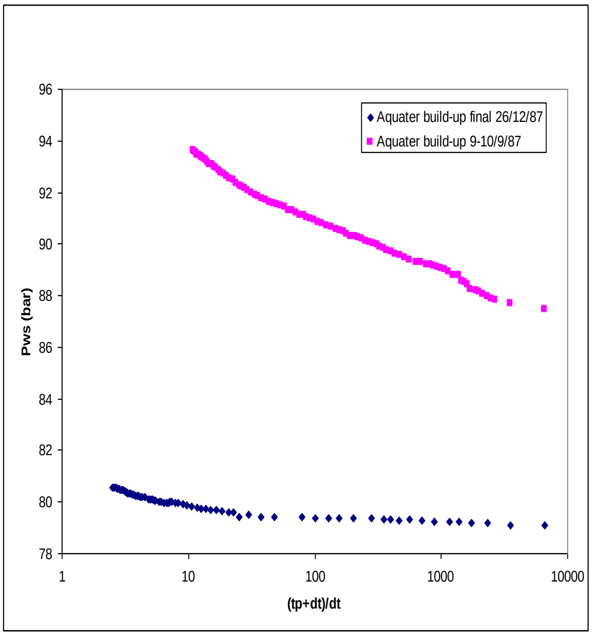

FIGURE 5: Well Asal 3 build-up tests

The two build-up tests (Figure 5) have been interpreted by the Horner method (Daher, 2005). The values of transmissivity (5 and 8 Dm) correspond more to the less permeable zone around well Asal 3 recognized by the drawdown tests. The measurements made during build-up period result from the global behaviour of the aquifer. That is why the calculated kh is less and indicate that the zone with kh of the order of 14 - 16 Dm has limited extension. The tests were made at the same level 1075m as the production tests and indicate that there is a large drawdown in the reservoir, around 10 bar-g.

The results of the build-up tests in well Asal 3 are presented in Table 3:

TABLE 3: Results of build-up test of Asal 3

date	q (ton/h)	Δq (ton/h)	m (Pa)	kh (Dm)
9.9.87	357-0	357	3.55E5	8
26.12.87	87-0	87	1.42E5	5

All the tests done in Asal 3 do not show a pressure variation with slope equal to 1 on a log-log graph. The effect of wellbore storage lasts only for a few minutes. It is not clear that the producing zones found in this borehole correspond to fractures. Although it is not definitively excluded considering the low skin factor and the geologic characteristics in the area, it seems that dual porosity behaviour is dominant.

3.4 Analysis well Asal 4

Well Asal 4 was drilled in 1988 to a total depth of 2013 m. The well is cased with 9-5/8" to 2013 m. An injection test was performed in well Asal 4 with an injection rate of 70 m^3/hour during 113 minutes. The variations of pressure were measured during and after the injection for 220 minutes. The fluid used for the injection was sea water thus having characteristics very different from those of the fluid in the reservoir. Nevertheless, the data allow proceeding to a valid interpretation by the classic well test methods.

The effect of wellbore storage is very important. After 1 ½ log cycle from the end of the unit slope line, the semilog straight line is expected to start. The infinity acting radial flow period is relatively limited and the distribution of the experimental data is not very regular. This can be explain by the difficulties in maintaining a perfectly regular flow rate. For this reason it is very difficult to use the match curve method. A log-log graph shows a straight line pressure with slope ½, thus indicating the presence of fractures.

The results of the injection test, the recovery and the Horner method (Table 4) show a low transmissivity (0.4-0.7 Dm). This value is very low with regard to that of Asal 3 and confirms the indications of injectivity indices calculated for Asal 4 and Asal 3, which are respectively 1.4 m^3/ h.bar and 100 m^3/h.bar. Production could not be initiated from well Asal 4 possibly due to this low transmissivity.

From the injection and recovery parts, estimation of skin factor is -4.6. Hence the well is good connected to the reservoir.

TABLE 4: Results from the injection test Asal 4

		Injection test		**Recovery test**		**Horner plot**	
date	**q (m^3/h)**	**m (bar)**	**kh (Dm)**	**m (bar)**	**kh (Dm)**	**m (bar)**	**kh (Dm)**
18.2.87	70	5.22	0.41	3.4	0.61	6.57	0.76

3.5 Analysis well Asal 6

Well Asal 6 was drilled in 1989 to a total depth of 1716 m. The well is cased with 9-5/8" to 388 m depth and 7 inch with liner between 364 and 919 m. It is open hole after 919 m until 1761 m.

Asal 6 was drilled about 300 m WNW of well Asal 3 and encountered another permeable zones below 1315 m which is the depth of Asal 3. Thus it can be expected to have productivity higher than Asal 3. Several multirate tests, drawdown and interference tests have been carried out in order to determine the characteristics of the borehole (Table 5) (Daher, 2005).

TABLE 5: Results of different pressure transient tests of Asal 6

			Semilog	
date	**q (tons/h)**	**Δq (ton/h)**	**m (Pa)**	**kh (Dm)**
4.10.88	Multiple		39.4 (bar/t/s)	6.2
5.10.88	Multiple		39.5 (bar/t/s)	6.3
5.10.88	65.2-78.3	13.1	0.13E5	8
1990	115.2-0 (Asal 3 shut-in)	115.2	1.22E5 (14m)	7.5

From the water level recovery in well A6 when well A3 was shut-in, a formation storativity value 6 10^{-9} m/Pa was obtain and as there is no skin factor s=0 for the interference test. From the drawdown test 5.10.88 we have an estimation of skin factor around 30. It is necessary to note the fact that several matching curves are possible and that this skin factor confirms this high positive value indicating decrease of the permeability of a formation due to the partial sealing of the invaded zone.

The transmissivities are of the same order as the global transmissivity calculated for Asal 3. On all these various tests the transmissivity for well Asal 6 varies in the range from 6.2 to 8 Dm. In the zone A1-A3-A6, the global transmissivity in the production interval down to 1600 m depth would thus be of the order of 4- 8 Dm.

4. Interpretation of output data

Four output characteristic curves were established for well Asal 3 (Figure 6). Two curves were established at the beginning and at the end of production test following the completion well by Aquater in 1987. Two others curves were realized by Virkir-Orkint Consulting Group Ltd in 1990 during the geothermal scaling and corrosion study. Each of these two periods of production lasted respectively 4 and 3 months.

Curve 1 (Aquater) represents the results obtained from a water-fed well feeding from a reservoir of low permeability. After four months, curve 2 is obtained (Aquater) in Figure 12. It indicates about 30 to 40% decrease in flow rate. The correlation between the second deliverability curve from Aquater 1987 and the first curve 1 from Virkir-Orkint is relatively good. Between these two periods, the well was shut-in. The second curve from Virkir-Orkint shows about 25 to 28% decrease in the flow rate compared to the earlier curve. Then, both phases of production of well Asal 3 show a decrease of 50 to 60 % in its initial output.

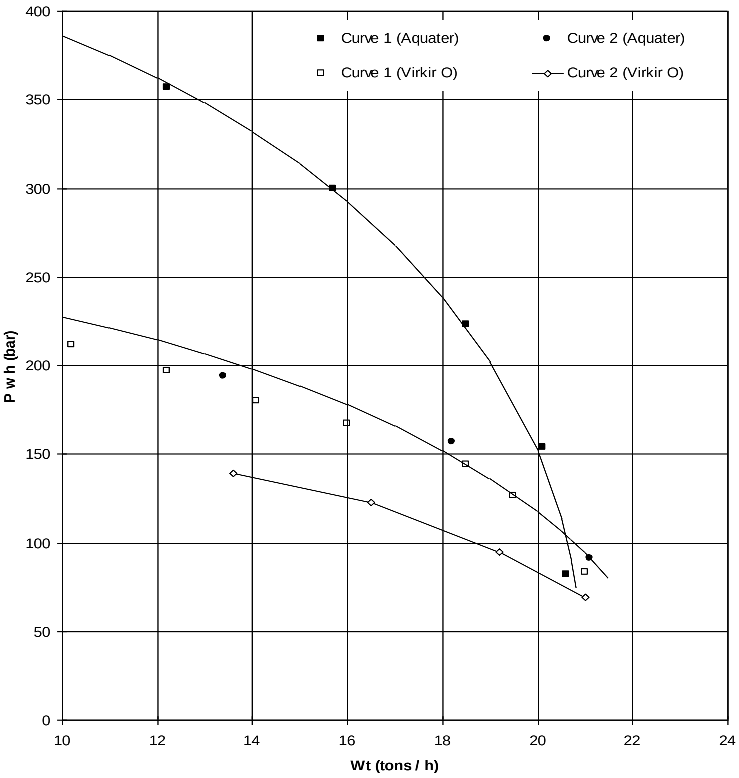

FIGURE 6: Characteristic curves of well Asal 3

Scaling and reservoir pressure drop explain the decrease in flow rate. At the flash zone between 650 to 750 m the diameter of the wellbore was reduced by about 20 mm. And between 600m and the wellhead, the diameter reduction was around 15mm. At low pressure in surface equipment the main deposition was $FeSiO_3$ and at high pressure i.e. down the well it was galena PbS (Figure 7).

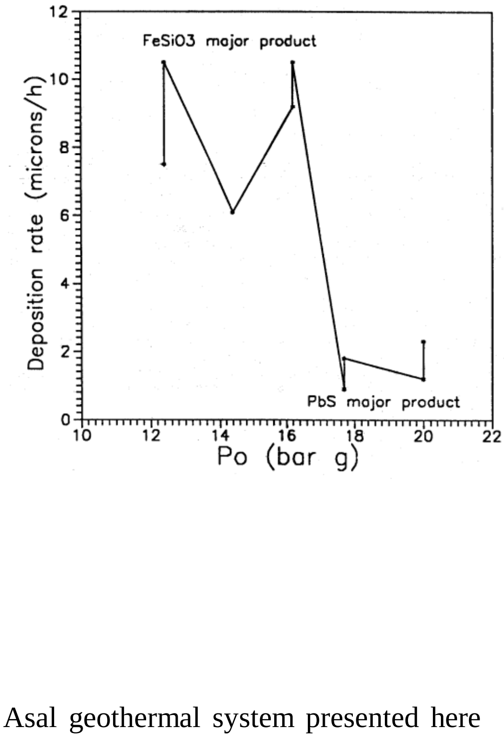

FIGURE 7: Scaling rate at different pressures in well Asal 3

6. CONCLUSIONS

The main results of the analysis of well test data from the Asal geothermal system presented here are the following:

- The permeability thickness of the deep geothermal reservoir is about 4-8 Dm.
- During long term exploitation, there is a large drawdown observed in the reservoir.
- The salinity of the deep reservoir fluid in the Asal geothermal field is high (120 g/l).
- Deposition of galena scale inside well Asal 3 while working at high pressure, between 18 and 20 bar-g, reduces the well radius and so decreases the discharge rate.

Based on the reports by Aquater (1989) and Virkir-Orkint (1990), and the results of this work the following recommendations are made:

- Extensive field tests should be performed to obtain more accurate data for estimating the actual size (geophysical exploration) and capacity of the reservoir.
- Since the results of the inhibitor tests made by Virkir-Orkint were relatively promising, laboratory study should be made in order to solve the problem of scaling by finding potential inhibitor chemicals available on the market.
- If the outcome of the above tests is positive, new production wells should be drilled.
- At depths between 400 and 600 m in the Asal area, there is apparently an extensive high- permeability aquifer encountered in all the wells, with a temperature of around 130°C and a salinity content of 50g/l. It is recommended that this aquifer be studied for its suitability for binary power production.

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