Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Geothermal Research in Vounalia Area, Milos Island (Greece), for Seawater Desalination and Power Production

Michael Fytikas[1], George Radoglou[2], Constantine Karytsas[3], Dimitrios Mendrinos[4], Antonis Vasalakis[5], Nikos Andritsos[6]

(1),(5)Department of Geology, Aristotle University of Thessaloniki,54124 Thessaloniki, Greece. (2)Gerling SDP, Sina 36, 10672, Athens, Greece. (3),(4)Centre for Renewable Energy Sources, 19th km Marathonos Ave., 19009, Pikermi-Athens, Greece. (6)Department of Mechanical & Industrial Engineering, University of Thessaly, 38334 Volos, Greece.

[1] fytikas@geo.auth.gr, [2] agrado@otenet.gr, [3] kkari@cres.gr, [4] dmendrin@cres.gr, [5] avasalak@geo.auth.gr, [6] nadrits@mie.uth.gr

Keywords: Milos, desalination, ORC.

ABSTRACT

In the framework of the joint geothermal research project MIDES, ten exploratory wells were drilled in Vounalia area of Milos Island in Greece. The aim of the project, which was partially financed by the European Commission, is seawater desalination and power generation using low enthalpy geothermal energy. Based on existing data and complementary fieldwork, the target area and the well sites were selected due to the high geothermal gradient (15-20 times the mean value) and the favorable geologic and tectonic conditions. The project aim was to produce enough quantities (exceeding 300 m³/h) of relative high-temperature geothermal water (80-100 ºC) in order to cover the thermal energy needs of the seawater desalination unit and the binary power generation plant. The wells are located in the rhyolitic-perlitic lavas of Vounalia lava-flow, which compose the youngest volcanic formation of the island (aged 80,000 years), and originated from the large Fyriplaka tuff-ring vent. The thickness of the formation was estimated and verified by the wells as 100-150 m. This specific formation is well fractured from the superficial cooling processes of the lavas and by resent-active tensional tectonics. All relevant well data and geothermal parameters (lithology, temperature, chemistry, flow rate yield) were identified during drilling and during production tests of a duration of 8-56 h. Injection tests were also realized at two wells with satisfactory results. The composition of the geothermal water is saline or more saline than seawater. The best production wells (F and G) yield 100m³/h of water each at 97 - 98.5ºC at the wellhead.

1. INTRODUCTION

Earlier geophysical, geochemical and deep drilling exploration performed on Milos Island proved the existence of a high enthalpy geothermal reservoir at depths 700-1400 m, which probably extends beneath the entire east half of the island (Fytikas 1977, Mendrinos 1988). Its exploitation attempt with a 2 MWe pilot power plant by the Greek public power company that took place in late 80s, failed due to technical and environmental problems associated with the high temperature and pressure, the chemistry and the hydrogen sulfide content of the deep fluids.

In the framework of the MIDES project, which was partially financed by the European Union through the "Energie" program (contract NNE5-1999-00041), relatively shallow (61-183m) geothermal drilling exploration was performed on Milos island, aiming in bringing to the surface sufficient quantities of low enthalpy geothermal fluids, needed for covering the fresh water demand of the island with seawater thermal desalination. The low enthalpy geothermal fluids encountered in Milos at shallow depths, are easier to control and do not exhibit the adverse environmental impact associated with the deeper high enthalpy fluids. The exploration took place in Vounalia area, which is located above the southeastern part of the deep geothermal reservoir, within the limits of the Milos Municipality geothermal concession. The location of Vounalia on Milos Island is shown in Figure 1.

Figure 1: Vounalia area of Milos island

2. GEOLOGICAL – GEOTHERMAL SITUATION

Milos belongs to the South Aegean active volcanic arc. Geothermal gradient is high on the island due to the recent volcanic activity (80,000 years ago) and the existence of molten magma in a few kilometers depth (Fytikas et al. 1989). Intense tectonics and frequent seismic activity complements the favorable conditions for the geothermal gradient on Milos, as has been proved by the 5 deep wells (1100-1350 m) drilled in the central east part of the island.

One of the reasons the area of Vounalia was selected for the geothermal exploration, was the high geothermal gradient identified by shallow exploratory boreholes drilled previously and by some wells drilled for irrigation purposes unsuccessfully. This geothermal gradient guarantied the existence of the required temperatures at shallow depths (100-200 m).

The intense hydrothermal alteration that took place in Milos resulted in the formation of vast bentonite and kaoline deposits, which are ideal for geothermal reservoir cap rock, and lock beneath them the thermal energy of high enthalpy geothermal fluids. They may also heat through conductivity and through fluid leakage the superficial low enthalpy aquifers.

Given the availability of the required temperature at shallow depth, the question was to find formations of high permeability, which can yield the necessary quantities of geothermal water. On the other hand, we wanted to avoid non condensable gases (mainly the annoying H_2S), high total dissolved solids (up to 150,000 mg/L at the separated liquid phase at atmospheric pressure) and high temperatures prevailing within the metamorphic basement or the overlaying neogene marine limestones. The older volcanic products in the area (0.5 to 3.5 million years old) that lay on top of the limestones are usually hydrothermally altered and do not have sufficient water bearing ability. Due to the absence of permeability heat flow through them is conductive.

Permeability in upper, younger and non-altered formations bearing water heated preferably by conduction, with limited mixing with the deeper geothermal fluids, which have high content in dissolved solids and possibly in dissolved gases, was an attractive solution. For this reason, the Vounalia area was selected, where rhyolithic-perlitic lavas from Fyriplaka complex are encountered, which are the most recent among all volcanic formations of Milos and nearby islands. These lavas form thick flows originating from Fyriplaka tuff ring, move NW and end in the bay of Milos.

Due to their high viscosity, the lavas form layers of thickness exceeding 100 m and are intensively fractured. Their fracturing occurred during the cooling process of the lavas. Intensive fracturing coupled with intensive active tectonics, resulted in extremely favorable conditions of permeability within this thick lava layer.

This lava layer forms a quite continuous aquifer with water level approximately at the sea level, as proved by all wells drilled for MIDES project. Although a conductively heated horizon was originally expected, water chemistry in some wells indicates also considerable mixing with deeper geothermal fluids, which is one of the components constituting the water of the aquifer, the other two being meteoric waters and seawater. This water type has similar characteristics with the hot springs encountered in some coastal areas of the island.

The aquifer temperature varies from 50-60ºC close to the north coast and to 80-100ºC at the interior. Well production temperature remains pretty constant during pumping, which can be attributed to the excellent water flow within the lavas, as expected. Flow rate yields differ from well to well due to different local conditions mainly. Wells that intersect fracture systems yield very high flow rates, higher than 100 m³/h, with very small water level decline and short recovery period. There are wells however, with flow rate yields lower than 20 m³/h. These flow rate values resulted from production tests of 56-h duration.

3. WELL DATA

3.1 Location, main features

For the purposes of the MIDES project, 10 wells have been already been drilled and one is going to be drilled in Vounalia. Their location on the geologic map is shown in Figure 2.

The first 3 wells, namely A, B and C are located in approximately 100 m elevation. Well B intersected a fractured zone before reaching the water level and drilling ended there. The intensively fractured zones encountered in each well are listed in Table 1, as identified from total mud losses during drilling.

Wells A and C are characterized by low permeability and production flow rate yields. Cost benefit analysis indicated that it is cheaper to drill other production wells in lower elevations, closer to the North coast, where the MIDES plant should be located, rather than connecting these wells.

The next four wells, namely wells D, F, G and H are located in medium elevation (40-60 m), are relatively close to the north coast of Vounalia, have high permeability, and flow rate yields approaching or exceeding 100 m³/h. They are best suited for production.

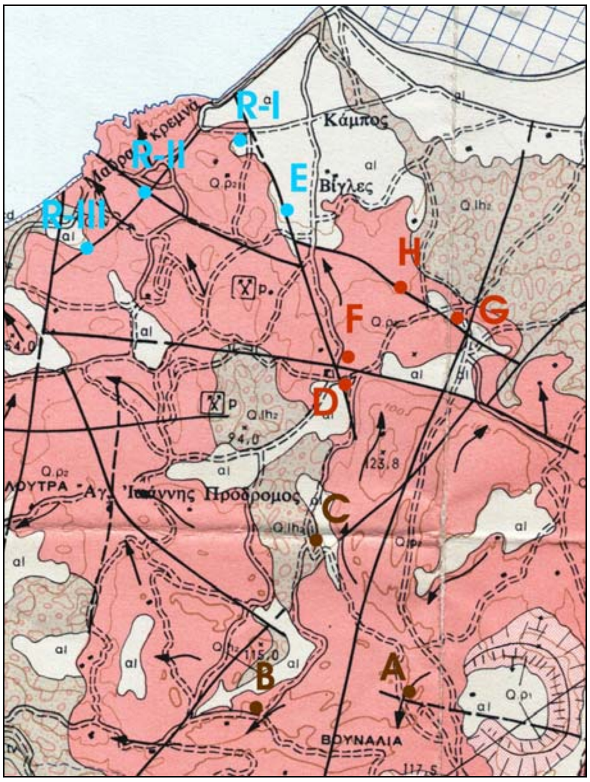

Figure 2: Location of geothermal wells in Vounalia area.

The remaining wells, namely E, R-I, R-II and probably the planned well R-III, are located at lower elevation (~20 m) close to the coast, have high permeability and flow rate yields, but lower temperature (50-60ºC). Within the MIDES project, they are best suited for reinjection.

3.2 Lithology, well profiles

The completion details of the wells are presented in Table 1 and their geologic profiles in Figure 3.

All wells were drilled until they either intersected an important fracture system below the water level that could yield high flow rates, such as wells F, G and R-II, or until they reached the bentonitic layers. Earlier production wells were cased by 8 inches casing, but later ones were cased by 10 inches one in order to allow the placement of a submersible pump of larger diameter and a corresponding increase in flow rate output. Water level was encountered near the sea level almost everywhere.

Regarding subsurface geology, the following three main layers have been identified: a) a top layer of rhyolitic lava flows with perlitic texture of thickness varying between 35 and 100 m, b) a layer of lahar which has either perlitic texture (wells A, C and D), or contains limestone fragments (wells E and G) and c) a deeper layer of hydrothermally altered tuffs, containing kaolin, iron hydroxides, and montmorillonite (bentonite), the percentage of which increases with depth. The latter is believed to be the cap rock of deeper pressurized fluids of high enthalpy.

3.3 Temperature profiles

Measurements of static temperature profiles took place in Vounalia wells, after allowing the temperature to stabilize for at least a few months after production tests. The only exception is well H, where available temperature data are limited to extrapolated temperatures during drilling. The results are presented in Figure 5. In general, these temperature profiles indicate the presence of two hot water permeable zones in most wells. The upper one, is located at the aquifer top, approximately at sea level elevation, and has a thickness of 10-20 m. Its temperature varies from 95ºC in well G to 53ºC in well R-II. This permeable zone lies on top of a second hot water zone, located at depths around 20 m below sea level. The latter is hotter in inland wells (A, C, D, F, G and H) with temperature 80-110ºC, and less hot in wells close to the coast (E, R-I and R-II) with temperature 40-50ºC. The temperature inversion evident in wells A and D and possibly in H, indicates horizontal flow of water within the second zone and the presence of a third deeper but of somewhat lower temperature permeable horizon there.

The static water level derived from these temperature measurements within all wells, is approximately at sea level, with the exception of well A, where is seems to be located 20 m higher, and well B, whose bottomhole lies well above the water level. The main production zones derived from temperature profiles of the wells, as well as from partial mud losses during drilling, are listed in table 1.

3.4 Production and reinjection tests

In every well except B and R-II, well completion was followed by an air-lift test, one day preliminary pumping for cleaning production zones, one day step pumping with three to five flow rate levels and finally one production test 56 hours long. Reinjection tests of 56 hours duration took place in wells R-I and R-II. Measurements of water level, flow rate and fluid temperature were taken at regular intervals. Representative results are shown in Table 1.

Production tests have demonstrated that wells D, F, G and H can deliver around 100 m³/h each of hot water 85-100ºC. Well D, due to its high productivity index, can probably yield even more, with its flow rate limited by the operating parameters of available submersible pumps. During production a rise in water level was observed in wells G and H, which can be attributed to downhole boiling. Wells closer to the coast, drilled for reinjection, have also flow rate yields of at least 100 m³/h each, but of 55-60ºC temperature. Water level recovery after production and reinjection testing was only a few minutes in all above wells, indicating very high permeability. On the other hand, interior wells A and C have low productivity indexes and flow rate yields 4 to 5 times less than the other wells.

3.5 Fluid chemistry

The chemical analysis of the fluids produced from the geothermal wells in Vounalia, is presented in Table 2. These analyses reveal that the geothermal fluids correspond to subsurface boiled altered seawater (A, F, R-I), or to its mixtures with local meteoric waters (wells C, D and E). The effect of high temperature conditions on seawater is evident by the marked increases in calcium, potassium, lithium and silica and by the significant decreases in magnesium sulfate and bicarbonate.

The chloride content of the water from the Vounalia wells varies between 11,200 ppm for well D, which is approximately half of the chloride content of local seawater, and 30,300 ppm for well R-I, value approximately 40% higher than the one of local seawater. This chloride content corresponds to diluted (well D) or boiled (well R-I) seawater. The latter can be attributed to the deep geothermal water flowing from Zefyria plain, where the main upflow zone of Milos geothermal field is located (Mendrinos, 1988). One explanation for the chemistry of the geothermal waters of Vounalia wells is the mixing of the three primary fluids available in Milos Island. These are: a) the deep geothermal water with 45,000 ppm chloride (Mendrinos 1988), b) seawater with 21,500 ppm chloride and c) meteoric waters with zero ppm chloride.

4. PROPOSED EXPLOITATION SCHEME

Water needs of Milos Island correspond to a seawater desalination unit delivering 75 m³/h of desalinated water. The multi effect distillation (MED) method is proposed for the desalination purposes, because it can use low grade thermal energy, such as hot water of temperature above 60ºC. Apart from thermal energy, the project requires electricity for the downhole pumps, the cooling seawater pumps, the desalination pumps (vacuum, distillate and brine), the monitoring and automation equipment, the lighting, etc. Overall power needs have been estimated as 470 kWe, which can be supplied by a geothermal ORC power plant. The cost benefit analysis performed for the MED device indicated that the optimum reinjection temperature is around 55ºC.

The flow chart of the proposed geothermal exploitation scheme for a seawater desalination plant, self sufficient in both thermal energy and electricity is drafted in Figure 4. The scheme includes four production wells with downhole submersible pumps delivering 360 m³/h of geothermal water of temperature 85-98ºC and four reinjection wells. Wells D, F, G and H are proposed for production, and wells E, R-I, R-II plus a new well R-III for reinjection. The ORC power generator and the MED seawater desalination unit are placed in cascade with the ORC first.

Cooling seawater flow rates have been estimated for the ORC unit at 540 m³/h, and for the MED device at 850 m³/h. Buried pre-insulated fiberglass piping with external polyethylene protection is proposed for the geothermal lines, and buried polyethylene piping for the seawater and desalinated water lines. A computer monitoring and control system is proposed. Power and data lines should connect the main plant with the wells and the seawater pumping stations.

5. ECONOMIC – SOCIAL CONSIDERATIONS

The MIDES geothermal cascade utilization scheme has been designed to be capable of producing 470 kWe from the Binary Cycle and 75 m³/h desalinated sea-water from the MED unit. The total cost of the application has been estimated as 5,200,000 €. The energy production and substitution has been estimated as 12,375 TOE per year. The water production cost of the MIDES plant has been estimated as 1.02 € per m³ of delivered desalinated water. Total annual operating costs including capital amortization are 816,033 €. After adding annual profits of 25%, the selling price of the desalinated water becomes 1.73 € per cubic meter. The thermal energy production cost for the MIDES project is just 0.0071 EURO/kWh_{th} including capital amortization.

When the project will be completed, the community of the island will certainly benefit from the availability of sufficient quantities of fresh desalinated water, which apart from raising local living conditions, will allow a large increase in islands' population during summer, boosting tourism and accelerating local development. Furthermore, the amount of reinjected water (360 m³/h at 55ºC) will contain enough energy for the downstream placement of additional geothermal energy uses, such as district heating, heating of greenhouses and thermal bathing.

CONCLUSION

Geothermal research performed in Vounalia area on Milos island, identified an aquifer of high permeability within the perlitic lavas and lahars extending from the sea coast to more than one kilometer inland, the thickness of which varies between 100m and 150m. Prevailing temperatures are 40-60ºC at a zone extending 0-500 m from the coast, with an evident temperature inversion within the wells. At a distance approximately 1 km from the coast the aquifer temperature rises to 80-100ºC. The wells drilled can produce 400 m³/h of 85-100ºC hot water, which is more than necessary for covering completely the energy needs, in terms of both heat and electricity, of a MED seawater desalination plant delivering 75 m³/h of desalinated water.

REFERENCES

Fytikas M.: Geological and geothermal study of Milos island. Institute of Geological and Mining Research, geological and geophysical research, Vol. XVIII, No 1 (1977).

Fytikas M., Garnish,J.D., Hutton, V.R.S., Stratoste, E., Wohlenberg,J.(1989): An integrated model for the geothermal field of Milos. Geothermics, 18, No 4, 611-621.

Fytikas M., Radoglou G., Karytsas C., Mendrinos D., Vasalakis A., Karampelas S., Darlagiannis N., Karavokyris A.: Geothermal Research in Vounalia Area (Milos Island) for Desalination and other Utilizations: Poster presented at the international conference "The South Aegean Volcanic Arc: Present Knowledge and Future Perspectives", 17-20 September (2003).

Karytsas C., Mendrinos D., Radoglou G.: Geothermal Field of Milos Island in Greece: Current Geothermal Exploration and Development, *CD-Rom Proceedings*, Start in eine neue Energiezukunft: 1 Fachcongress Geothermischer Strom, Neustadt Glewe, 12-13 November (2003).

Mendrinos D.: Modeling of geothermal fields in Greece, Master of Engineering Thesis, University of Auckland, New Zealand, (1988).

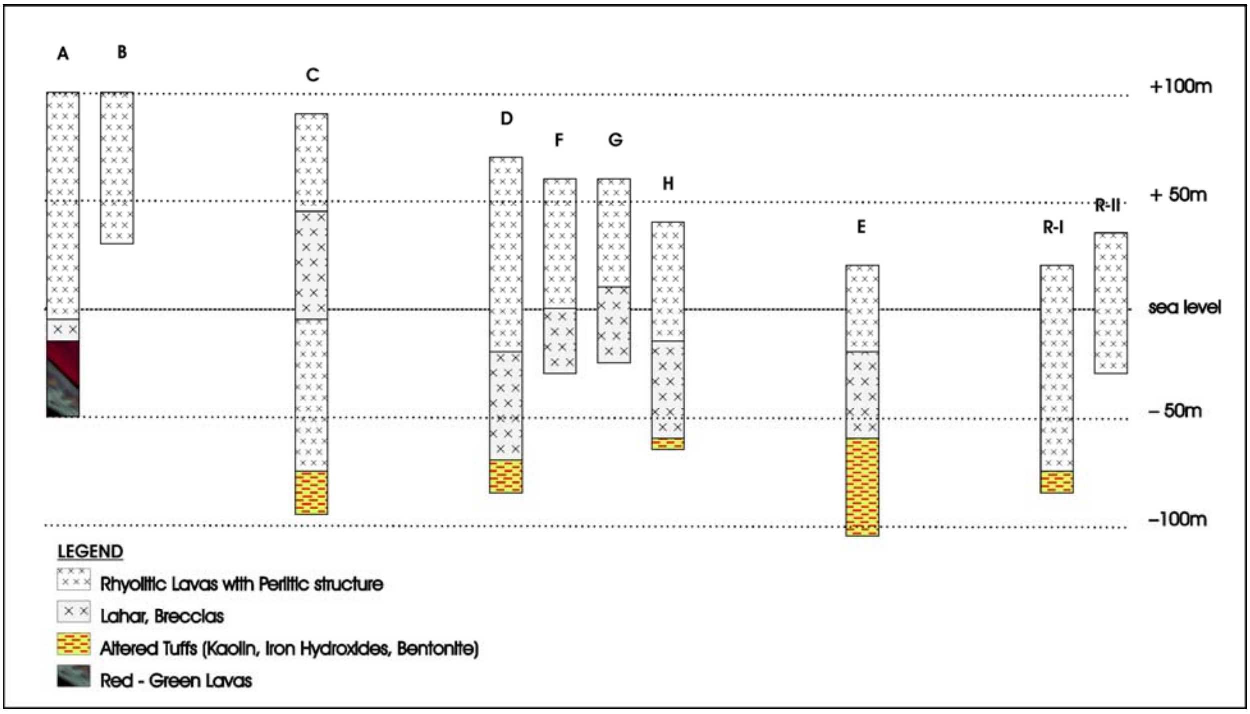

Figure 3: Geological profiles of Vounalia wells

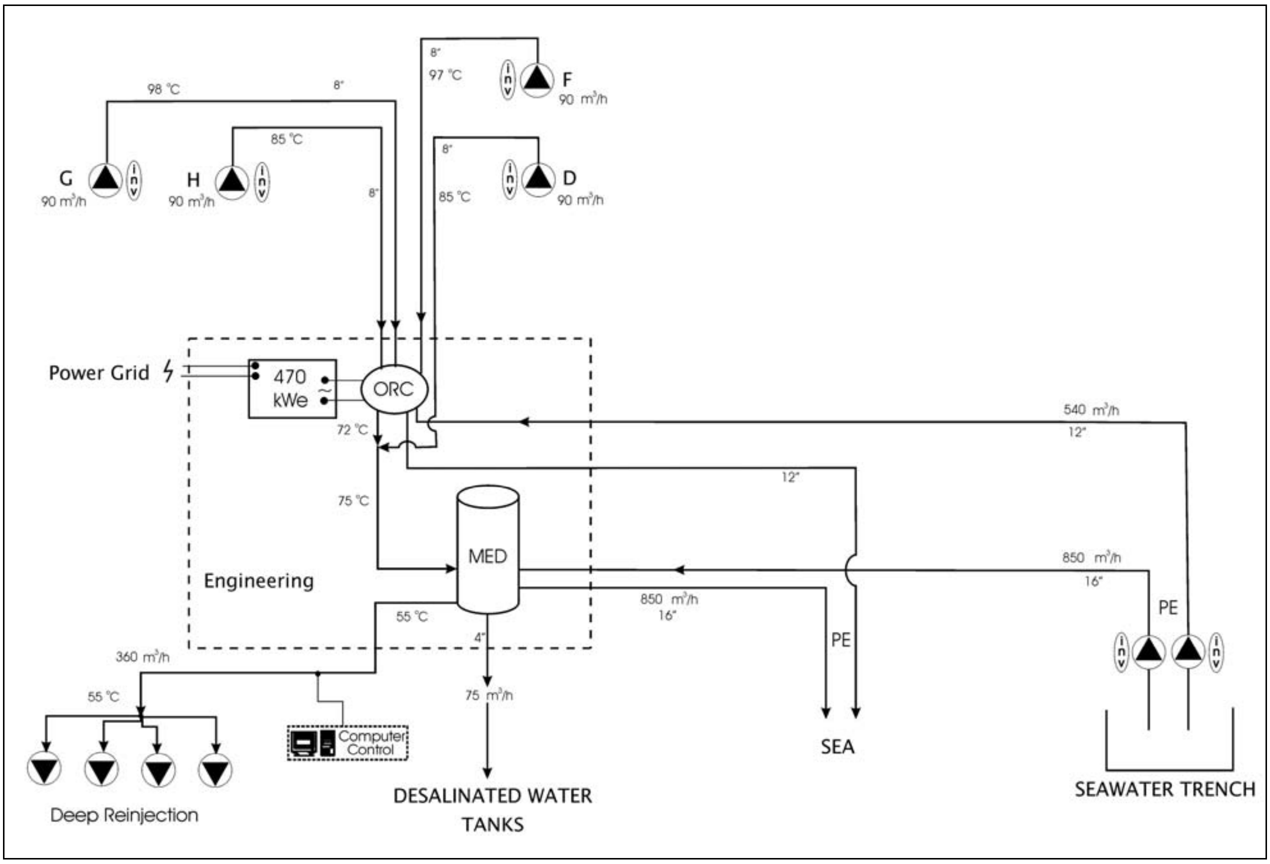

Figure 4: Flow chart for the proposed ORC power generation and seawater desalination plant.

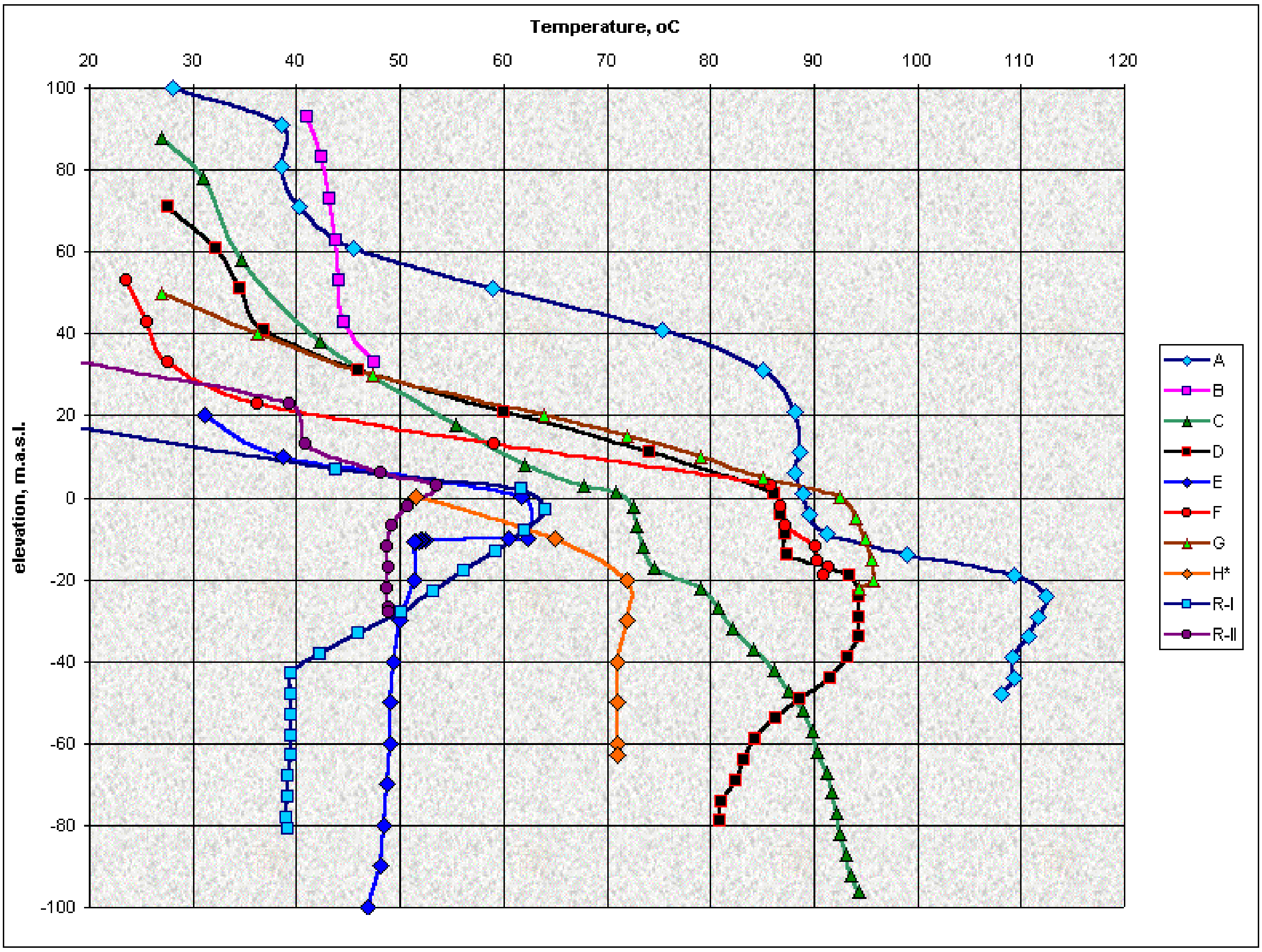

Figure 5: Static temperature profiles of Vounalia wells. *(*extrapolated during drilling, measured production temperature: 87ºC)*

Table 1: Milos-Vounalia geothermal wells summary

Well	well bottom, m	casing /liner diameter, inches	casing shoe m	static water level, m	measured Flow Rate, m^3/h	flowing water level, m	productivity (injectivity) index m^3/h per m	water flowing Temp., ºC	fault zone	production zones, m
A	150	8’’	149	74	20	125*	0.4	98	–	80-110, 120-150
B	71	8’’	67	–	0	–	–	–	65	–
C	184	8’’	183	86	25	132	0.5	84	–	90-100, 160-170
D	158	8’’	152	65.4	80	65.8	200	85	138	65-80, 90-110 125-150
E	125	8’’	122	19	100	30	9.1	55	–	30-40, 60-120
F	89	8’’	82	57	100	55, 18**	n.a.	97	74	55-85
G	85	10’’	82.,5	57	95	39**	n.a.	99	80	80-85
H	105	10’’	84	38	60	45	8.6	87		80-100
R-I	102	10’’	98	15,2	90 70***	17 1***	50 (5)***	60	–	18-100
R-II	63	10’’	61	27.1	90***	19***	(11)***	n.a.	59	30, 40-63

* estimated, ** due to boiling, *** reinjection

Table 2: Chemistry of water produced from Milos-Vounalia geothermal wells

Geothermal Well	A	C	D	E	F	R-I
Temperature, ºC	97	89	85	55	97	60
pH at 25ºC	6.86	6.36	6.69	7.75	7.20	7.50
Conductivity at 25ºC, mS/cm	55.1	43.9	25.2	32.8	57.1	69.0
total Hardness, mg $CaCO_3$	4,800	3,900	1,700	2,510	5,230	5,940
non carbonate Hardness, mg $CaCO_3$	4,650	3,850	1,520	2,440	5,160	5,785
total dissolved solids, g/L	42.3	33.2	19.0	25.2	43.6	54.1
Density at 15ºC, kg/L	1.0288	1.0217	1.0114	1.0160	1.0300	1.0330
Chemical species conc. in mg/L						
Na^+	12,200	9,400	5,280	7,600	12,600	15,100
K^+	2,620	1,800	1,150	1,370	2,700	3,780
Ca^{2+}	1,515	1,350	725	850	1,520	2,120
Mg^{2+}	192	120	85	94	348	1,560
Fe^{2+}	0.4	30	0.7	0.6	1.1	0.4
Mn^{2+}	19	12	6	6.9	12.9	26.5
Sr^{2+}	23	18	10	14	23	32
Li^+	30	24	14	15	23	33
Zn^{2+}	0.5	5.2	1.2	0.4	3.3	0.3
Cu^{2+}	0.1	0.5	1.2	–	–	–
Pb^{2+}	0.01	0.02	0.07	0.04	0.04	0.04
Cd^{2+}	–	–	–	0.002	0.001	0.002
Ni^{2+}	–	0.015	–	–	–	–
Cr	–	–	–	–	–	–
NH_4^+	6.4	3.1	8.8	4.3	6.2	11.0
Cl^-	25,125	19,900	11,200	13,700	23,900	30,300
F^-	1.3	0.5	0.9	0.6	0.8	0.5
HCO^-	56	59	82	85	90	86
HS^-	–	–	–	–	–	–
SO_4^{2-}	310	275	170	1,350	2,180	850
NO_3^-	0.8	1.3	3.1	1.0	1.2	0.8
NO_2^-	0.04	0.4	0.01	0.5	0.7	0.01
PO_4^{3-}	–	–	–	–	–	–
As	0.12	0.03	–	0.02	0.03	0.05
B	28.0	25.1	11.4	14.0	25.6	30.3
SiO_2	158	202	162	104	138	142