Correlation Between Liquid Saturation and Physical Phenomena in Vapor-dominated Geothermal Reservoirs

Franco D'Amore[1] and Alfred Truesdell[2]

1 Inst. Intemat. Ricerche Geotermiche, Pisa Italy
2 Consultant, Menlo Park, Calif U. S. A.

Key words: vapor-dominated reservoirs, liquid saturation, grid method, gas reactions

ABSTRACT

The "grid" method of study of gas reactions in vapor-dominated reservoirs indicates the temperature and steam fraction of the in situ fluid. When other observations, including steam flow, gas/steam, boron and $\delta^{18}O$, are combined with the results of grid calculations, processes induced by exploitation such as cold recharge (natural or injected) and steam migration are clearly delineated. These interpretive methods are of great value in reservoir management of steam fields.

INTRODUCTION and MODEL DESCRIPTION

As vapor-dominated geothermal reservoirs produce only steam to wells, geochemical studies are limited to gases and volatile salts. This work concentrates on the calculation of the in situ steam fraction and temperature from gas compositions using the "grid" method and the combination of these calculations with other data to indicate a range of reservoir processes. The grid method has been proved to be a valid tool for analyzing processes occurring in two phase geothermal reservoirs (e.g. Giggenbach, 1980; Calore et al., 1982; D'Amore et al., 1982; D'Amore et al., 1983; Truesdell et al. 1984; Bertrami et al., 1985; D'Amore and Truesdell, 1985; D'Amore and Pruess, 1986; Nieva et al. 1987; D'Amore and Truesdell, 1988; Arnorsson et al., 1990; and others). We *start* from two chemical equilibria involving the most commonly measured gas species (H_2, H_2S, CO_2 and CH_4) and H_2O:

$$CH_4 + 2\,H_2O = 4\,H_2 + CO_2 \qquad (1)$$

$$H_2 + 3/2\,FeS_2 + 2\,H_2O = 3\,H_2S + 1/2\,Fe_3O_4 \qquad (2)$$

Applying the law of mass action to these equilibra and following all considerations reported in Giggenbach (1980), DAmore et al. (1982) and DAmore and Truesdell (1985 and 1988), the following two equations can be obtained:

$$4\log(H_2/H_2O) - \log(CH_4/CO_2) = FT$$
$$= -15.35 - 3952.8/T + 4.635 \log T + f_1(y, B_i) \qquad (3)$$

$$3\log(H_2S/H_2O) - \log(H_2/H_2O) = HSH$$
$$= 6.231 - 6223.2/T - 0.412 \log T + f_2(y, B_i) \qquad (4)$$

where:
- FT and HSH are the symbols used in the diagrams reporting these functions;
- temperature T is in K;
- y is the in situ steam fraction. It has a positive value when a fraction of steam is present at equilibrium with the liquid phase; it has a negative value when a fraction of steam is irreversibly lost from the original liquid (Giggenbach, 1980; D'Amore and Truesdell, 1985);
- Bi is the vapor-liquid distribution coefficient, a known function of temperature, as described in Giggenbach (1980) and D'Amore and Truesdell (1988).

For a two phase system (D'Amore et al., 1982 and D'Amore and Truesdell, 1985):

$$f_1(y,B_i) = 4\log[y+(1-y)/B(H_2)] + \log[y+(1-y)/B(CO_2)] - \log[y+(1-y)/B(CH_4)] \qquad (5)$$

$$f_2(y, B_i) = 3\log[y + (1 - y)/B(H_2S)] - \log[y + (1 - y)/B(H_2)] \qquad (6)$$

From the computed values of y and temperature we can calculate the in situ liquid saturation:

$$S_l = (1-y)\, v_l / [y\, v_s + (1-y)\, v_l] \qquad (7)$$

where v_l and v_s are respectively the specific volume for liquid water and steam.

The graphical solution of he system given by equations 3 and 4 genererates a plot. In it the chemical parameters FT and HSH are represented as coordinates, while the physical parameters temperature and steam fraction y produce a grid inside the diagram. This system can be successfully used both for positive or negative values of y (e g. Giggenbach, 1980, D'knore et ai., 1983)

Several limitations and assumptions must be taken into account when using this method (e.g. D'Amore et al., 1983 and DAmore and Pruess, 1986):
1) the chemical reactions considered must exist and reach themodynamic equilibrium for all chemical species considered;
2) all the chemical species considered, including H_2O, must be in both chemical and phase equilibrium;
3) steam is considered to be in phase equilibrium with liquid water in the reservoir;
4) no mass gain or loss is allowed in the original equilibrated system;
5) fluid at the wellhead generally consists of a mixture of fluids coming from various volumes or sources of the reservoir with different chemical and physical characteristics. What we obtain through the application of this method are integrated resultant values of the in situ temperature and steam fraction y for all these different sources (D'Amore and Celati, 1983; DAmore and Pruess, 1986). D'Amore and Truesdell (1979) describe some of these sources in vapor-dominated systems. Exploitation can induce production from new regions of the reservoir having different fluid composition;
6) differences in chemical composition of the fluids from different reservoir regions can also exist due to variations in mineral compositions between different reservoir layers (e.g. production of extra CO_2 not equilibrated with other gases), or to the entry of a separated high-pressure gas phase (formed because of condensation phenomenon close to a border of the field) into the exploited low-pressure reservoir. This will cause y values to be overestimated
7) differences or changes with time of the source temperature. Although this method allows the calculation of a change in temperature with time in a local portion of the reservoir, it is unable to discriminate between different portions having different temperatures;
8) it is assumed there is no re-equilibration of the chemical species from the source or sources to the wellhead;

The aim of this work is to present some examples, limited to the vapor-dominated fields of The Geysers and Larderello, of the application of the method for some physical phenomena affecting the reservoir fluid composition. These phenomena produce correlations between computed in situ steam fraction (y) or liquid saturation (Sl) and other parameters of the well, such as gas/steam ratio, isotopic composition of steam, and flow rate.

APPLICATIONS

In both The Geysers and Larderello, we observe a large variability in the computed in situ steam fraction for several wells at a given time (Fig 1, fiom DAmore and Truesdell, 1985, and Fig. 2). This can be due both to different sources of fluid having different contents of liquid with respect to total fluid and to different parameters locally affecting the rock matrix, such as permeability, porosity, heat and mass balance.

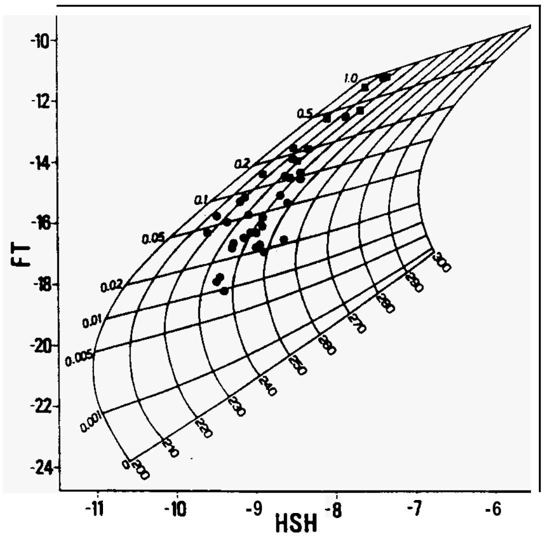

Fig. 1. "Grid" diagram applied to The Geysers geothernial field (from DAmore and Truesdell, 1985). Squares refer to wells located in the central zone after years of production, circles refer to wells located in the southeastem zone of the field under initial conditions. FT and HSH are defined by Eqs. 3 and 4 respectively.

In Fig. 1 circles refer to wells located in the southeastern zone of The Geysers and squares, to wells in the central zone. All these wells produce superheated steam and are not affected by reinjection. In spite of the relatively small range in temperatures computed by the use of the grid, 235±15°C, the range of y values spans more than two orders of magnitude, from 0.008 to 0.90. This distribution is not random, but seems to be roughly related to the time of exploitation of

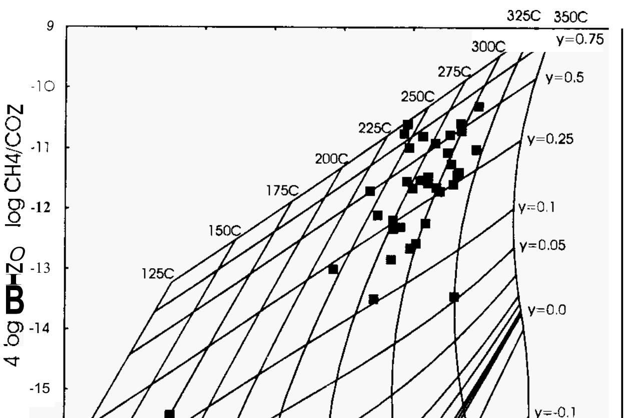

Fig. 2. "Grid" diagram applied to Larderello wells unaffected by injection.

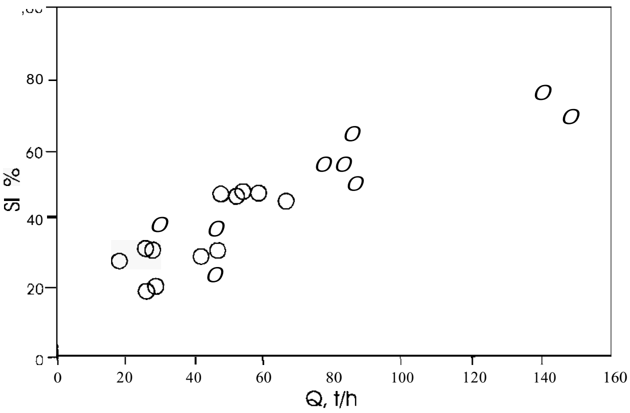

Fig. 3. Measured values of flow-rate Q (tons/h) vs the liquid saturation Sl from computed steam fraction and temperature values for wells of The Geysers in the southeastern zone of the field.

the wells represented in the figure. In fact, all wells located in the newly-exploited SE zone, are positioned in the lower half part of the diagram with y values not exceeding 0.1. On the contrary, wells located in central area, which had been under production for several years, show quite high y values, despite the same order of computed temperature as the southeastern wells.

In Fig. 2, 1978 data for several wells of Larderello, before any injection effect, located in different zones of the field, have been plotted. These wells have been exploited for several decades. While they show y values greater than 0.1, similar to those of the oldest wells of The Geysers, their computed temperatures yield an average close to 280°C. Temperatures close to 300°C have been measured in Larderello at depths of the order of 1500 meters (Cappetti et al., 1985).

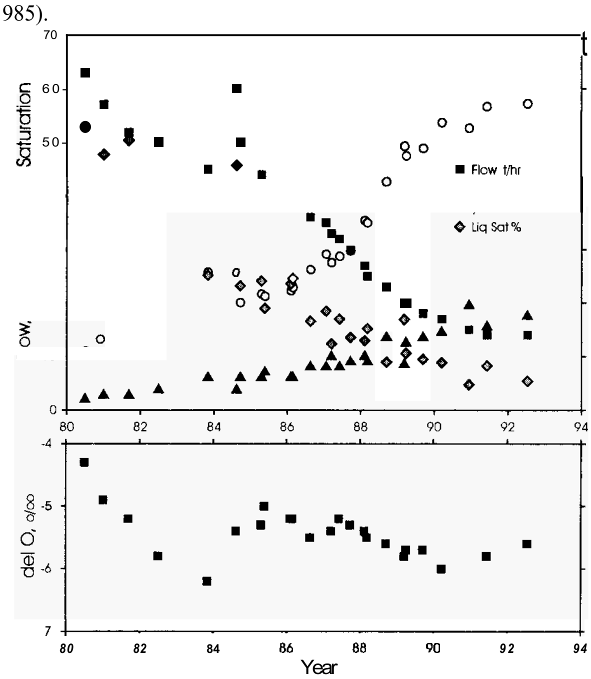

Fig. 4. Geysers well DV-3. Measured values of flow-rate Q (tons/h), gas/steam molar ratio and computed values of steam fraction y and liquid saturation Sl vs time.

In the above examples, the wide variability in y values, despite relative homogeneity in computed temperature, suggests that y values can be locally related to the relative amount of liquid stored in the reservoir, and so potentially exploitable. An example of this is given for samples located in the southeastern zone of The Geysers. We can report for these samples the measured values of flow-rate (tons/h) vs the liquid saturation (Sl in %) (Fig.3) computed fiom the y and temperature values (the circles of Fig.1). A logarithmic correlation is evident as for the Larderello samples reported in DAmore and Pruess (1986).

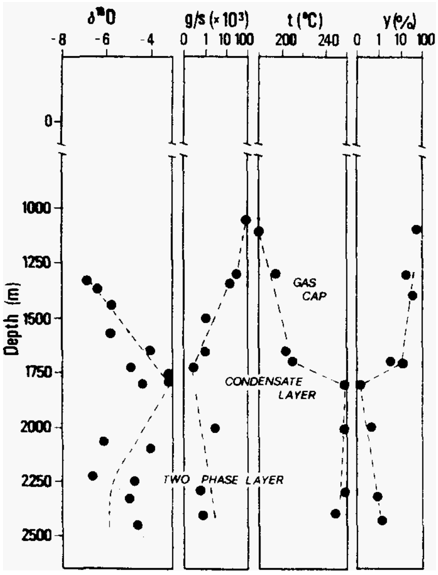

Fig. 5. Distribution with depth oftneasured $\delta^{18}O$ ofthe steam, gas/steam molar ratio and computed temperature (t°C) and steam fraction (v) values from Geysers wells during drilling.

Geothermal reservoirs are dynamic stores of heat and fluid. For vapor-dominated systems, fluid supply is critical as we can observe for DV3, a typical Geysers well. This well, located in the southeastern part of the field, has been monitored for about 12 years for physical and geochemical parameters (Table 1). Computed steam fraction (y) and liquid saturation (SI) values are compared to other parameters: F ^{18}O of the produced steam, the gas/steam ratio and the steam flow rate (Fig. 4). The temporal trends observed can be explained by the "multiple sources" model described by D'Amore and Truesdell, 1979. In this example two main sources are assumed to be responsible for the variations observed in Fig. 4. The first source may be an upper, liquid-rich layer formed by condensation, produced by local upward heat losses, of steam from the underlying two-phase layer, which constitutes the main second source.

During the first period of exploitation (1980-83), the main contribution to the produced steam came in large amount from the first source. The condensate layer shows low y values (and high liquid saturation) producing the observed high flow rates from a very permeable portion of the reservoir. The gas content in this upper layer is very low with respect to total water because of the relatively low solubility of gases in the liquid phase (as compared to the vapor phase). With time, the upper condensate layer becomes exhausted and steam is then produced mainly from the main two-phase reservoir (1984-92 period). The fluid therein is characterized by much higher y values and low liquid saturation which is correlated with the observed progressive lowering of the flow rate and drawdown of the available liquid in the reservoir. The high content of gas in 1992 (about six times respect to the original fluid) can be related to the high steam contents in the two-phase reservoir (in the two-phase zone there is "room" for the gas). The flow-rate decline after 12 years of production is close to 80%. The FD of the steam is constant (close to - 55‰) indicating no reinjectate returns. The values of $\delta^{18}O$ become two units more negative in the first four years of production, then almost stabilize. If we suppose that the first production was from a upper condensate liquid layer, and then production was mostly from a two-phase layer, rich in steam, the equilibrium fractionation beween the two phases at 240±10°C is 2%a

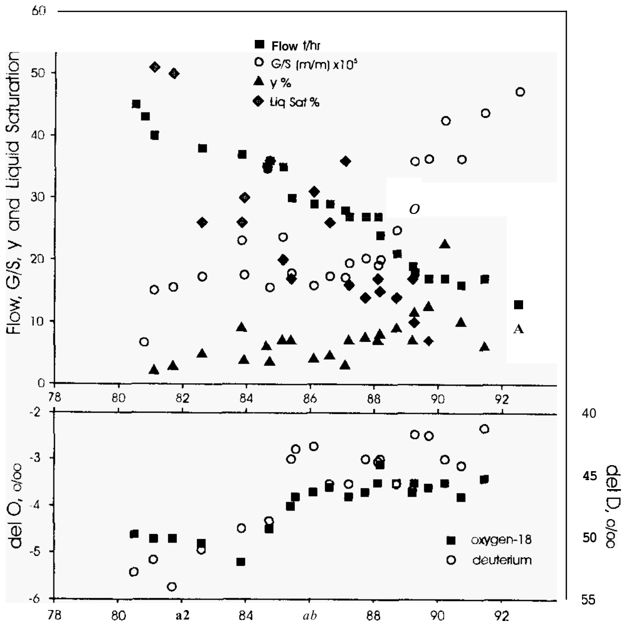

Fig. 6. Geysers well McKinley 1. Measured values of flow-rate Q(tons/h), gas/steam as molar ratio, $\delta^{18}O$ and FD of the steam and computed values of steam fraction y and liquid saturation SI vs time.

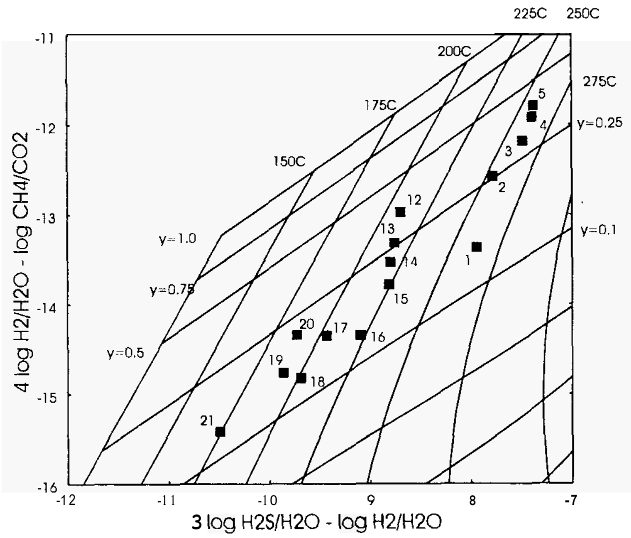

Fig. 7. "Grid" diagram application for the well Guiducci (Castelnuovo zone, Larderello) from 1939 to 1982. Numbers indicate sampling order.

Deep drilling of wells at The Geysers allowed multiple fluid sampling from the main steam entries (Box et al., 1987) confirming most of the sequence postulated by DAmore and Truesdell (1979) and observed for well DV3 in this work and in Larderello (D'Amore and Pruess, 1986) at least for the first years of production. It was possible to measure and to calculate some parameters during drilling, which permit us to distinguish different chemical and physical characteristics of the fluid at different depths. Three different fluids have been encountered, as shown in Figure 5. The shallowest one is composed of a mixture of gas and steam, with y values close to 1, at measured and computed temperatures lower than 200°C and very negative values of $\delta^{18}O$. These isotopic values of the steam are produced by fractionation from the underlying layer. Moreover gas can accumulate and reequilibrate in this shallow layer. This volume of the reservoir is generally exhausted after a few weeks or months of production. The underlying layer has quite opposite characteristics. The fluid is made of almost pure liquid, with y values close to 0, at measured and computed temperatures close to 250°C and much less negative values of $\delta^{18}O$. This fluid has been interpreted as corresponding to that portion of the reservoir previously called the condensate layer. The deepest fluid seems to have all the characteristics corresponding to a two-phase fluid having about the same temperature of the middle layer, but higher values of y and gas content, and $\delta^{18}O$ values more negative by about 2‰.

Well McK1, also located in the southeastern part of The Geysers field, in a portion of the reservoir with relatively low permeability, after few years of production started to be affected by reinjection returns (Table 1). FD values after about six years of production increased of about

10‰ ; at the same time the values of $\delta^{18}O$ after an initial trend twards more negative values (as for well **DV3),** increasd up to **1.5%** (Fig. 6). The isotopic composition of the injector was **δD = -11±2‰** and **$\delta^{18}O$ = +2.3±1.0‰**. A mass balance using the δD and $\delta^{18}O$ values indicates a maximum fraction of reinjectate returns close **25%.** With respect to the "normal" well **DV3,** we observe (Fig. 6) a smaller increase in steam fraction or a decrease in liquid saturation. This corresponds to a lower flow-rate decline (about 60%) probably due to the inflow of reinjected water. The gas/steam ratio increased only about three times.

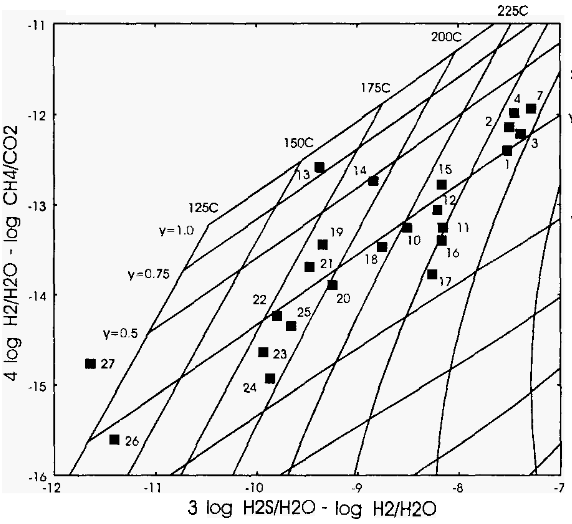

Fig. **8.** "Grid" diagram application for the well Tommi (Castelnuovo zone of Larderello) from **1939** to **1978.**

In the south-eastern part of Larderello field (Castelnuovo) several wells have been affected by slow natural recharge and inflow of cold water from the sorrounding aquifers and from the nearby outcrops of permeable limestone structures (Celati et al., **1973; 1991;** Panichi et al., **1974;** Ceccarelli et al., **1987).** Up to **100** Tritium Units were still present in the area in the seventies. This inflow eventually produced the cooling of that portion of reservoir with a critical decline in steam flow rate for many of the old shallow wells (less than 500 m deep). The general trend observed in Figures **7** and **8** for two typical wells (Guiducci and Tommi) is consistent with the inflow of cold water from these recharge areas into the exploited reservoir. This behavior contrasts with that of the S. Vincenzo well discussed later (Fig. **9).** Temperature decline **of** the Castelnuovo wells (measured downhole) is from 250-275°C in the first period **(1939-1955)** to values lower then **200°C** after **1970.** The **gas/steam** ratio, after an initial increase, after **1955** starts to decrese regularly down to very low values (Fig. **10).**

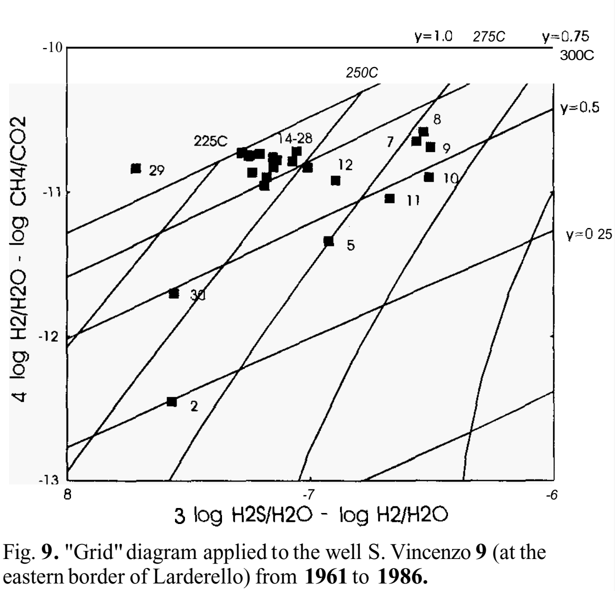

Fig. **9.** "Grid" diagram applied to the well S. Vincenzo **9** (at the eastern border of Larderello) from **1961** to **1986.**

Moreover the large variation in **NH3/N2** ratio with time from about one to more then **50,** as the decline in H2S content, is compatible with a large decrease in temperature in the reservoir (D'Amore et al., **1993).**

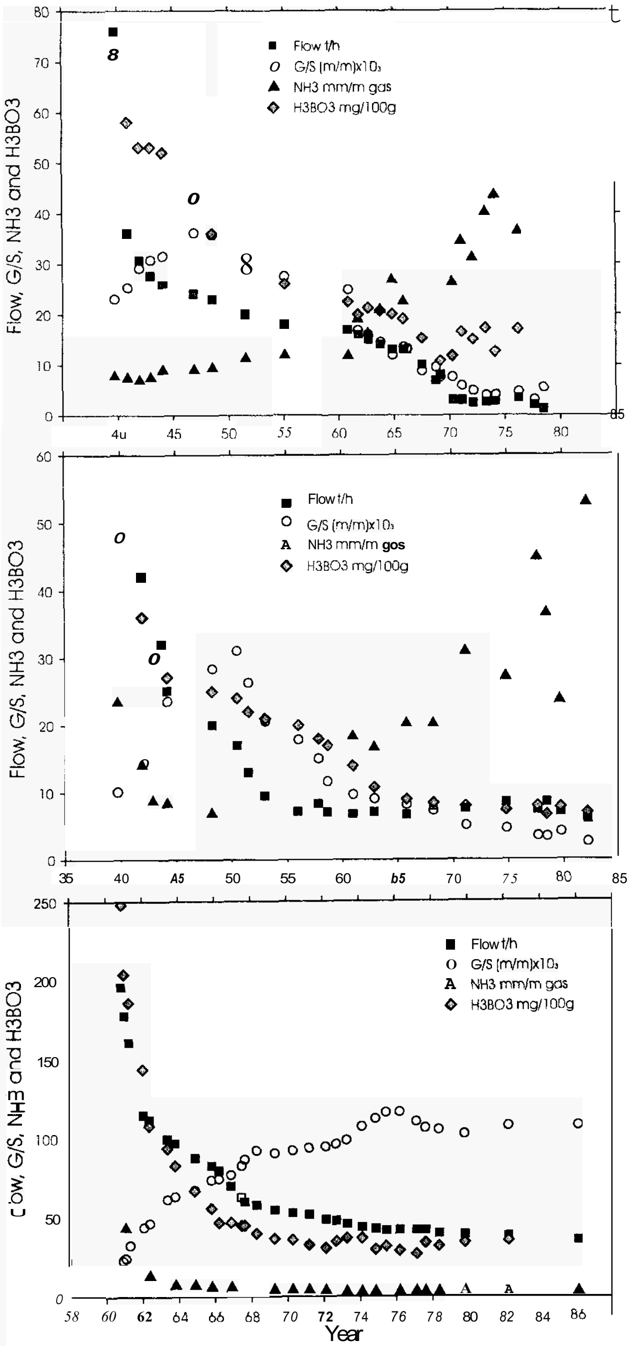

Fig. **10.** Flow-rate, gas/steam (mole ratio), **NH3** in the dry gas (mole %), and boron content in the condensed steam (mg/kg **H3BO3)** vs time for Larderello wells a) Tommi, b) Guiducci and c) S. Vincenzo **9.**

The **S.** Vincenzo wells, with a vertical depth exceeding **1 km,** are located in the extreme easthern portion of Larderello field. The local reservoir has a high measured temperature (about 260°C) and the wells are still good producers after many years of production. They show very high gas/steam ratios, up to 0.6 moles gas/mole steam or about **750** liters of **gas** per kg of steam. When the grid method is applied **to** these fluids it generally produces extremely high values of steam fraction (y), absolutely incompatible with the observed production. It is evident thdt an external source of gas affects these results. Indeed, considering the observations from DAmore and Truesdell **(1979)** this behaviour can be explained. These wells are located at the edge of the reservoir, where a cold, low permeability barrier is present. From the center of the field towards this border, it has been demonstrated that a condensation path exists. This locally increases the gas content in the nearby reservoir. In the cold zone at about 3 km east from these wells, the well Sesta 1, with a temperature of 100°C at a depth of about 1 km, produced in 1978 only cold gas at a pressure of about 25 bars (or, with adiabatic decompression, - 20°C at a WHP of 1 bar). From this we can postulate an inflow of high pressure cold gas in that portion of the exploited reservoir with low pressure in the large fractures (about 6 bars in the late seventies). In the well S.Vincenzo 9 (Figures 9 and 10) despite very high values of y (>0.5) in the grid, the computed temperatures are very close to that of the reservoir, averaging **250±15°C.** Flow-rate in 1986 (after 26 years of production) was still 35 tons/h. At the beginning of production, with a very high flow-rate (> 150 tons/h), the gas content was low. When the system depressurized because of production, exotic gas started to flow into the reservoir from the cold border.

CONCLUSIONS

In this paper we review the early studies of fluid supply to Larderello and Geysers, two vapor-dominated reservoirs, and compare steam fraction computed values or liquid saturation values with very different reservoir conditions. A knowledge of the liquid water saturation in different parts of a geothermal reservoir and its variations with time are of crucial importance for rational field exploitation. In fact estimates of drawdown or cooling phenomena in different parts of the reservoir, in different periods, are extremely useful in establishing optimal drilling and reinjection programs. Neither geophysical well logs nor classical well-testing techniques have yet managed to determine precisely the steam fraction in the reservoir.

On the other hand methods that utilize fluid composition and its variations over space and time, as shown in this and earlier papers, also appear promising because of their low cost. The method proposed here tries to utilize in a simple way both physical processes and chemical and phase equilibria concepts to obtain values of equilibrium temperature, and in situ steam fraction or liquid saturation in tlie reservoir. The application of this method is facilitated by the use of suitable graphs with "grids" which allow the unique determination of both parameters.

Despite successful results, some limitations exist in the application of the method. The necessary conditions are the achievement of chemical and phase equilibria inside a unique main source of fluid, and the lack of large mass gain or loss from the original fluid in out of equilibrium conditions. The results reported here encourage the authors to extend tlie application of fluid geochemistry to more complex geothermal systems in which these special boundary conditions are not fulfilled.

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Table 1a. Analytical and calculated data for steam from well DV3 of The Geysers

	date	months	flow rate	gas/steam	CO2	H2S	NH3	N2	CH4	H2	Ar	∂18-O	∂D	FT	HSH	y	t(grid)	SI
			tons/h	x 1 Million							x 1000							
	01 to 06/84		shut down															
1	80/07/01	7	63	103	33.0	24.4	12.3	1.30	2.00	29.3		-4.3	-54.8	-16.86	-9.28	0.015	246	0.603
2	80/10/60		60	125														
3	81/01/02	13	57	177	40.8	20.0	11.9	1.29	2.59	24.4		-4.9	-53.4	-16.26	-8.99	0.025	252	0.503
4	81/09/08	21	52	201	45.5	22.0	7.85	1.70	2.82	26.0		-5.2	-58.5	-15.95	-8.78	0.03	255	0.47
5	82/06/30	30	50	216	51.1	17.2	6.50	1.83	1.57	21.8		-5.8	-56.4	-15.8	-8.96	0.04	250	0.375
6	83/11/02	47	45	251	44.3	16.7	6.80	1.62	1.88	28.7	17.7	-6.2	-54.8	-15.2	-8.99	0.06	240	0.244
7	84/08/14	56	60	250	44.2	22.5	8.68	1.32	1.20	22.1	16.8	-5.4	-56.7	-15.46	-8.49	0.04	260	0.42
8	84/09/20	57	50	194	41.3	17.6	9.10	1.08	1.29	29.6	13.4			-15.46	-9.16	0.055	239	0.257
9	85/04/18	64	44	210	43.3	16.8	12.0	1.12	1.03	25.7	13.9	-5.3	-57.5	-15.45	-9.09	0.05	240	0.281
10	85/05/23	65	41	206	39.8	16.7	9.89	0.95	1.36	31.2	9.42	-5.0	-55.0	-15.3	-9.2	0.065	235	0.212
11	86/02/05	74	41	216	37.6	17.3	9.97	1.91	1.57	32.0	22.6	-5.2	-55.3	-15.26	-9.12	0.075	235	0.187
12	86/02/25	74	38	222	38.5	17.8	10.5	1.90	1.79	30.2	15.7	-5.2	-55.9	-15.36	-9.04	0.065	240	0.228
13	86/08/19	80	36	256	45.3	14.6	8.84	1.24	1.39	28.7	11.4	-5.5	-56.4	-15.02	-9.15	0.08	232	0.168
14	87/01/21	85	35	285	44.9	15.4	10.6	0.74	1.15	27.2	7.98			-14.85	-8.56	0.08	238	0.185
15	87/03/16	87	33	269	43.8	14.4	9.53	0.68	1.22	30.4	9.62	-5.4	-58.0	-14.79	-9.15	0.09	230	0.146
16	87/06/04	90	32	281	48.8	13.7	8.55	1.02	1.54	26.4	10.6	-5.2	-53.8	-15.02	-9.11	0.085	233	0.162
17	87/09/21	93	30	291	50.4	12.3	8.45	0.83	1.43	26.7	5.78	-5.3	-57.0	-14.89	9.23	0.09	232	0.151
18	88/02/09	98	27	347	51.2	12.3	8.66	0.55	1.55	25.8	3.55	-5.4	-54.0	-14.67	-9.06	0.095	232	0.143
19	88/03/07	99	25	343	52.2	12.4	7.88	0.71	1.63	25.1	3.97	-5.5	-55.1	-14.76	-9.05	0.09	232	0.151
20	88/09/13	105	23	420	51.1	11.9	7.48	0.44	1.62	27.5	2.93	-5.6	-56.0	-14.25	-8.97	0.14	227	0.089
21	89/03/14	111	20	486	57.9	11.3	7.58	0.92	1.50	20.7	0.84	-5.8	-57.0	-14.66	-8.91	0.095	238	0.159
22	89/03/31	111	20	468	55.0	11.2	8.36	0.42	1.52	23.6	1.98	-5.7	-58.0	-14.27	-8.89	0.13	230	0.102
23	89/09/12	117	18	482	53.8	11.3	7.20	0.51	1.77	25.4	5.06	-5.7	-53.0	-14.17	-8.88	0.15	229	0.086
24	90/03/19	123	17	529	55.8	11.0	7.04	0.31	1.62	24.3	2.50	-6.0	-54.1	-14.03	-0.82	0.16	232	0.084
25	90/12/14	132	15	519	55.6	10.2	6.19	0.27	1.95	28.5	1.55	-5.8	-58.1	-13.87	-9	0.18	220	0.059
26	91/06/10	138	14	568	57.7	10.7	6.57	0.34	1.60	23.1		-5.8	-58.1	-13.97	-8.76	0.17	230	0.076
27	92/07/15	151	14	573	58.4	8.39	7.70	0.56	1.86	23.1	3.87	-5.6	-52.8	-14.01	-9.08	0.2	221	0.052

Table 1b. Analytical and calculated data for steam from well McKinley1 of The Geysers

	date	month	flow rate	Gas/steam		H2S	NH3	N2	CH4	H2	Ar	∂18-O	∂D	FT	HSH	y	t(grid)	SI
			tons/h	x 1 million	CO2						x 1000							
	1 to 7/84		shut down															
1	80/07/01	7	45									-4.6	53.1					
2	80/10/16	10	43	61														
3	81/02/04	14	40	145	23.4	18.4	8.13	15.7	9.47	32.1		-4.7	-52.1	-16.89	-9.39	0.02	242	0.51
4	81/09/09	21		150	36.0	23.4	8.0	4.45	8.69	34.1		-4.7	-54.3	-16.53	-9.07	0.025	252	0.50
5	82/08/05	32	38	167	18.6	18.7	5.1	13.6	1.94	40		-4.8	-51.3	-15.72	-9.34	0.05	234	0.26
6	83/11/03	47	37	225	23.7	15.5	7.49	9.5	2.20	41.5	163	-5.2	-49.6	-15.09	-9.34	0.065	249	0.26
7	83/11/29	47		170	35.7	17.8	6.96	8.23	1.43	29.7	143			-15.79	-9.26	0.045	238	0.30
8	84/08/13	56	35	141	52.2	12.1	7.05	4.24	2.41	21.9	57			-16.1	-9.79	0.03	230	0.35
9	84/09/20	57	36	150	35.7	19.1	8.07	6.33	1.67	29.1	81	-4.5	-49.0	-16.11	-9.27	0.035	240	0.36
10	85/02	62	35	231	38.7	16.1	6.66	8.07	1.21	29.1	108			-15.19	-9.12	0.072	237	0.20
11	85/05/24	65	30	173	26.1	14.1	7.40	12.2	1.84	38.1	169	-4.0	-44.0	-15.57	-9.66	0.07	225	0.17
12	85/07	67										-3.8	-43.2					
13	86/02/05	74	29	153	29.6	17.5	9.05	11.0	2.04	30.7	158	-3.7	-43.0	-16.15	-9.39	0.04	235	0.31
14	86/08/07	80	29	168	25.7	15.2	9.55	7.3	1.96	30.1	83	-3.6	-46.0	-15.92	-9.48	0.045	230	0.26
15	87/01/30	85	28	166	39.3	16.0	8.88	6.99	3.13	25.6	57			-16.39	-9.36	0.035	240	0.36
16	87/03/16	87	27	189	37.0	13.5	8.86	4.75	2.02	33.8	66	-3.8	-46	-15.52	-9.59	0.07	223	0.16
17	87/09/21	93	27	197	39.9	13.3	9.35	3.06	1.45	32.9	45	-3.7	-44	-15.31	-9.56	0.08	222	0.14
18	88/02/10	98	27	186	42.0	13.9	9.26	2.55	1.42	30.8	35	-3.5	-44.2	-15.5	-9.52	0.07	226	0.17
19	88/03/07	99	24	195	40.0	13.4	8.71	3.15	1.66	33.0	38	-3.1	-44	-15.38	-9.56	0.075	223	0.15
20	88/09/13	105	21	242	42.5	12.3	8.17	2.36	2.42	32.3	32	-3.5	-46	-15.18	-9.47	0.082	222	0.14
21	89/03/14	111	19	277	49.1	12.6	7.77	2.55	1.91	26.1	33	-3.7	-46.5	-15.15	-9.23	0.078	230	0.17
22	89/04/04	112	18	354	45.9	10.2	7.09	3.23	3.42	30.1	41	-3.5	-42	-14.76	-9.36	0.11	221	0.10
23	89/09/12	117	17	358	46.8	9.28	6.87	2.8	3.42	30.8	37	-3.6	-42.1	-14.69	-9.45	0.13	213	0.07
24	90/03/16	123	17	420	41.5	9.40	5.37	2.89	2.91	37.9	36	-3.5	-44	-14.04	-9.41	0.2	200	0.03
25	90/09/20	129	16	358	47.7	10.9	6.65	1.72	3.03	29.0		-3.8	-44.5	-14.74	-9.13	0.1	228	0.13
26	91/06/11	138	17	432	53.4	10.3	5.62	3.69	6.00	21.0	44	-3.4	-41.5	-15.22	-9.01	0.08	240	0.19
27	92/07/09	151	13	467	48.3	10.6	6.72	4.42	5.36	24.5	51	-4.1	-42.8	-14.81	-8.98	0.09	235	0.16

Table 2. Analytical data for steam from wells Tommi, Guiducci and S. Vincenzo of Larderello

Well	n	year	flow rate	gas/steam	CO2	H2	H2S	CH4	N2	NH3	H3BO3	TWB	TWH	
			tons/h	molar x 1000							mg/kg	℃	℃	
TOMMI	1	39/09	76	23.4	95.3	1.15	0.86	1.26	0.58	0.78	715		185	
	2	40/11	36	25.6	95.1	1.23	0.84	1.3	0.67	0.74	580		192	
	3	41/12	31	28.7	95.3	1.03	0.80	1.2	0.6	0.70	530		195	
	4	42/12	28	30.3	95.3	1.09	0.75	1.1	0.7	0.75	530		192	
	5	44/01	26	31.0						0.89	520		196	
	6	46/11	24	35.3						0.9	430			
	7	48/07	23	34.9	96.2	0.91	0.73	0.85	0.54	0.94	360		195	
	8	51/07	20	28.1						1.13	310			
	9	55/02	18	26.7						1.19	260		189	
	10	60/11	17	24.1	97.4	0.51	0.30	0.40	0.23	1.18	225		189	
	11	61/10	16	16.1	95.6	0.89	0.62	0.73	0.25	1.91	200		195	
	12	62/09	15	15.3	96.0	0.90	0.62	0.4	0.51	1.62	213		194	
	13	63/10	14	13.7	95.9	1.2	0.30	0.27	0.21	2.09	207		191	
	14	64/11	13	11.1	94.8	1.43	0.55	0.33	0.20	2.67	200		190	
	15	65/11	13	12.7	95.7	1.00	0.75	0.15	0.15	2.25	191		190	
	16	66/03	13	12.4	97.9	0.81	0.71	0.25	0.13				191	
	17	67/07	10	8.04	97.8	0.94	0.93	0.19	0.10		153		188	
	18	68/10	7	8.8	98.1	1.06	0.62	0.22	0.17				177	
	19	69/03	8	6.8	97.7	1.36	0.51	0.20	0.18		108		165	
	20	70/04	3	6.8	95.4	1.03	0.50	0.18	0.23	2.62	117		140	
	21	71/02	3	5.1	94.0	1.59	0.59	0.20	0.14	3.45	165		131	
	22	72/02	2.5	4.1	94.8	1.32	0.50	0.14	0.14	3.13	150		130	
	23	73/04	2.6	3.2	93.8	1.32	0.53	0.13	0.22	4.03	173			
	24	74/02	2.8	3.3	93.8	1.06	0.51	0.12	0.16	4.36	126			
	25	76/03	3.4	3.9	94.1	1.28	0.57	0.13	0.32	3.64	171			
	36	77/08	2.1	2.3	97.7	1.08	0.20	0.15	0.23				117	
	27	78/06	1.3	4.7	98.4	0.97	0.10	0.25	0.23				104	shut
GUIDUCCI	1	39/10	89	9.52	93.2	1.54	1.25	1.01	0.65	2.33	480		183	
	2	41/12	42	14.5	94.3	1.62	1.08	1.08	0.67	1.32	360		185	
	3	42/12	32	20.8	94.4	1.40	1.02	1.04	0.67	0.87	300		186	
	4	44/03	25	22.9	94.5	1.50	1.05	1.10	0.66	0.83	270		202	
	5	48/03	20	27.8	94.1	1.35	0.90	1.16	0.68	0.69	250		204	
	6	50/06	17	30.5							240		208	
	7	51/06	13	25.7							220		198	
	8	52/12	9.5	20.0							210		191	
	9	55/12	7.2	17.3							200		190	
	10	57/10	8.4	14.5							180		184	
	11	58/08	7.1	11.1							170		187	
	12	60/12	6.8	9.12	94.8	1.75	0.75	0.58	0.32	1.83	140		184	
	13	62/11	7.1	8.50	95.5	1.41	0.70	0.41	0.40	1.67	108		190	
	14	65/10	6.7	7.60	95.5	1.30	0.71	0.31	0.18	2.02	90		193	
	15	68/03	8.0	6.75	95.7	1.20	0.74	0.25	0.12	2.02	85		195	
	16	71/02	7.6	4.51	94.5	1.20	0.78	0.18	0.15	3.09	80		195	
	17	74/10	8.5	4.00	95.0	1.42	0.69	0.22	0.10	2.71	74		195	
	18	77/08	7.4	2.90	93.0	1.48	0.71	0.21	0.09	4.49	80		190	
	19	78/06	8.6	2.81	94.0	1.45	0.63	0.15	0.07	3.66	67		190	
	20	79/09	7.1	3.5	95.2	1.48	0.61	0.15	0.09	2.36	78		180	
	21	82/02	6.0	1.98	92.9	1.34	0.48	0.12	0.06	5.29	70		170	shut
S.VINCENZO 9	1	60/11	196	20.9							248	251	209	
	2	61/01	178	22.5	92.8	1.00	0.81	0.67	0.36	4.36	204	254	218	
	3	61/04	161	30.5							186	254	221	
	4	62/01	115	41.8							144	250	224	
	5	62/05	112	44.2	95.5	0.97	0.84	0.70	0.70	1.34	108	251	230	
	6	63/05	100	59.5							94	252	231	
	7	63/10	97	61.1	95.8	1.06	0.92	0.75	0.78	0.66	83	253	232	
	8	64/11	88	65.1	95.8	1.05	0.90	0.80	0.80	0.64	67	254	234	
	9	65/10	83	71.5	96.1	0.90	0.82	0.80	0.88	0.54	56	255	236	
	10	66/03	80	72.3	96.8	0.80	0.78	0.85	0.70		47	252	234	
	11	66/11	70	74.7	96.4	0.72	0.65	0.89	0.80	0.51	47	252	234	
	12	67/06	63	80.4	97.2	0.71	0.52	0.85	0.68		45	250	232	
	13	67/08	60	84.4							45	250	234	
	14	68/04	58	90.0	97.3	0.63	0.37	0.90	0.79		40	248	231	
	15	69/04	55	88.4	97.5	0.71	0.40	0.86	0.51	0.42	37	250	235	
	16	70/04	53	90.0	96.9	0.72	0.36	0.90	0.72	0.40	36	246	233	
	17	71/03	52	91.6	96.9	0.70	0.36	0.92	0.75	0.39	33	246	231	
	18	72/02	49	92.4	96.9	0.70	0.35	0.90	0.83	0.37	31	246	231	
	19	72/09	48	94.0	97.4	0.67	0.35	0.85	0.77		35	246	232	
	20	73/04	46	96.4	97.2	0.60	0.35	0.85	0.78	0.27	37	246	233	
	21	74/02	44	105	97.2	0.57	0.37	0.84	0.79	0.27	37	245	232	
	22	74/11	43	110	97.1	0.58	0.31	0.87	0.83	0.28	30	245	230	
	23	75/06	42	114							32	245	230	
	24	76/03	42	114	96.9	0.58	0.34	0.96	0.87	0.27	29	244	230	
	25	77/02	42	108	97.0	0.59	0.35	0.97	0.86	0.28	27	244	227	
	26	77/08	42	104	97.0	0.60	0.34	0.98	0.85	0.28	34	244	224	
	27	78/05	40	103	96.9	0.62	0.35	0.96	0.88	0.27	32	244	227	
	28	79/10	39	100	96.8	0.62	0.33	1.04	0.90	0.29	34	243	225	
	29	82/03	38	105	96.8	0.61	0.22	1.11	1.07	0.21	35	243	225	
	30	86/01	35	105	97.0	0.37	0.21	1.11	1.05	0.26				