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

Reservoir Response to Exploitation at the Miravalles Geothermal Field

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Keywords: Pressure Decline, Miravalles Geothermal Field, Costa Rica

ABSTRACT

The Miravalles Geothermal Field has been producing electric energy since March 1994. It has provided steam for Unit 1 (55 MWe, installed 1994), a wellhead unit (5 MWe, 1995), Unit 2 (55 MWe, 1998) and Unit 3 (29 MWe, 2000). A 19 MWe "bottoming cycle" plant (Unit 5) that was completed in January 2004 has brought the total installed capacity in Miravelles to 163 MWe. The performance of the field in terms of the behavior of reservoir pressure due to exploitation is described in the following sections. The field has successfully supplied the steam needed to generate the installed capacity over the first ten years of exploitation.

1. INTRODUCTION

Reservoir pressure has been measured regularly at the Miravalles geothermal field since 1994. Static water levels (hydraulic levels) have also been recorded in many geothermal wells, providing an indirect measurement of the reservoir pressure. With these measurements, it has been possible to evaluate the changes in the reservoir pressure that have occurred since the first power plant unit was commissioned.

Detailed histories of production and injection for individual wells and different sectors of the field are also available, making it possible to assess the response of the reservoir to exploitation.

In order to interpret the reservoir pressure response as new units came on line, three periods were defined: March 1994 to July 1998 for Unit 1, August 1998 to February 2000 for Units 1 and 2, and March 2000 until April 2004 for Units 1, 2 and 3. The average pressure decline, hydraulic levels and injection volumes have been estimated for these three periods.

2. THE MIRAVALLES GEOTHERMAL FIELD

Miravalles, the most important Costa Rican geothermal area, is located on the southwestern slope of the Miravalles volcano. The present field extends over an area of more than 21 km^2, about 16 km^2 of which are dedicated to production and 5 km^2 to injection. The temperature of the water-dominated geothermal reservoir is about 240 ^{0}C. Fifty-three geothermal wells have been drilled to date. They include observation, production and injection wells; their depths range from 900 to 3,000 meters. Individual wells produce enough steam to generate between 3 and 12 MWe each; injection wells accept between 70 and 450 kg/s of separated geothermal fluids each.

At present, the total steam delivered to the power plants is about 280 kg/s. Nearly 1,330 kg/s of residual geothermal water (separated brine) are sent to the injection wells, which are distributed in four sectors of the field: the northern, southern, eastern and southwestern sectors (Moya and Castro, 2004).

3. PRESSURE DATA

The available pressure data from the Miravalles field were obtained from the pressure observation wells and measured hydraulic levels. As new units have been commissioned over time, the number of observation wells has been reduced.

3.1 Pressure Monitoring

Pressures in the reservoir have been monitored using portable equipment obtained from B. G. Technologies (1994-1998) and from Pruett Industries (1998).

Pressure measurements are made in different wells (in different parts of the field), in order to observe the response of the reservoir during production and injection of geothermal fluids. Figure 1 shows the record of pressure decline in the geothermal wells indicated by the monitoring equipment (Castro, 2002, 2003 and 2004).

3.2 Hydraulic Levels

Hydraulic levels have also been measured in available wells, in order to observe the pressure response in the reservoir. The wells in which it has been possible to measure hydraulic levels are shown in Figure 2 (Castro, 2002, 2003 and 2004).

4. INJECTED WATER IN THE RESERVOIR

Table 1 shows the amount of water injected (during the three periods) in the different injection wells at the Miravalles geothermal field (Nietzen, 2004).

Figures 3, 4 and 5 show the relative volumes of water injected in the different wells during the periods indicated previously. The size of the circle around each well corresponds to the volume of brine injected.

Figure 3 (Unit 1, 1994-1998) shows that most of the water was injected in wells PGM-22, PGM-24 (both to the west of the production zone) and PGM-26 (to the south). During this period, more water was injected in the western sector than in the southern sector. Figure 4 (Units 1 & 2, 1998-2000) indicates that the main injection wells remained the same as before; nevertheless, the injection into wells PGM-16, PGM-28 and PGM-51 made the southern sector the most important injection zone during this period (Moya and Castro, 2001). In Figure 5 (Units 1, 2 & 3, 2000 – June 2004) it can be observed that the southern sector continues to serve as the principal injection zone.

Figure 6 summarizes the injection that has been taking place in each of the injection wells, and Figure 7 shows the amount of water injected in the different sectors of the field.

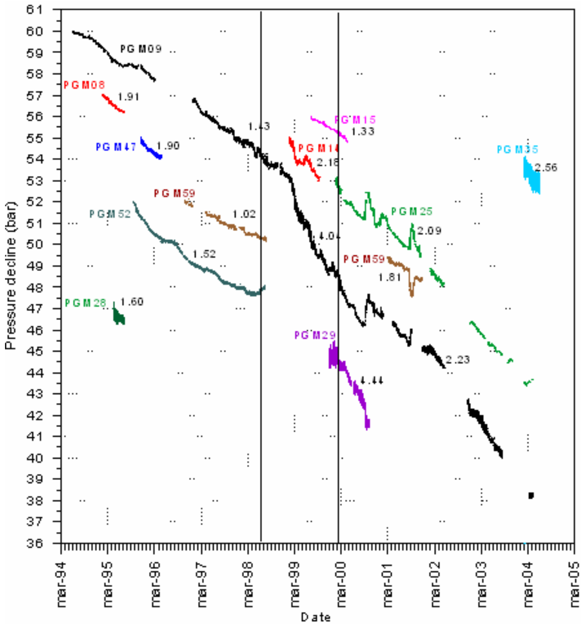

Figure 1: Pressure Decline in Observation Wells.

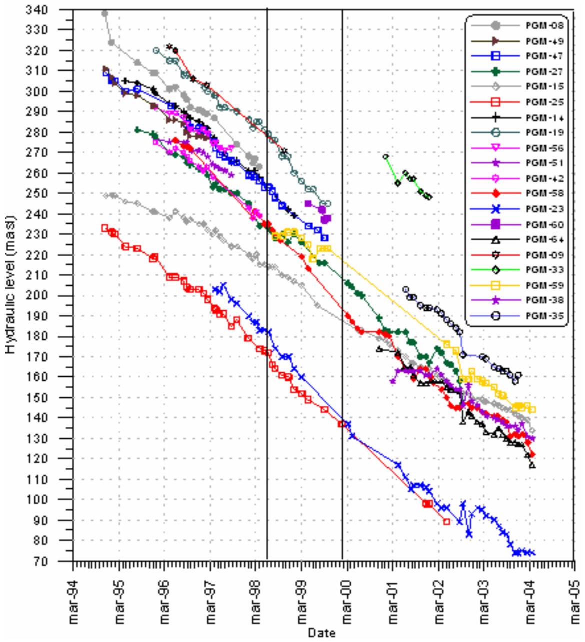

Figure 2: Hydraulic Levels in Geothermal Wells.

5. PRESSURE DECLINE

Table 2 shows the pressure decline in the reservoir interpreted from recorded monitoring data as well as hydraulic level data. Where possible, an average of the two measurements is shown for each of the periods of the study.

It can be seen that the pressure decline rate values derived from the two sources of data (monitored pressure and measured hydraulic levels, both in bar/year) are similar. As an example, in well PGM-08 (Period 1) the values were 1.91 and 2.11 bar/year. The pressure decline rates for periods 2 and 3 also showed similar values for the two sets of data.

In order to characterize the pressure decline in the reservoir, the average pressure decline rates observed in the wells during the three periods were contoured. Figures 8, 9 and 10 indicate the patterns of pressure decline for the first, second and third periods respectively.

Table 1: Injection at the Miravalles Geothermal Field.

	Cumulative Injected Mass (Ton)		
Well	Unit 1 3/94 - 4/98	Unit 1 & 2 3/94 - 2/00	Unit 1, 2 & 3 3/94 - 6/04
PGM-02	5,434,187	6,226,648	6,313,655
PGM-04	11,830,803	16,110,152	31,164,495
PGM-16	11,972,635	17,953,270	26,886,364
PGM-22	25,953,888	34,892,262	52,763,834
PGM-24	23,826,162	30,162,595	50,303,901
PGM-26	23,146,007	29,260,198	50,140,988
PGM-27	1,021,481	1,021,481	1,304,768
PGM-28	4,584,148	12,995,335	59,378,115
PGM-51	0	8,645,554	30,635,711
PGM-56	0	12,385,961	50,853,562
PGM-59	0	625,280	2,944,847
Total	**107,769,310**	**170,278,736**	**362,690,240**

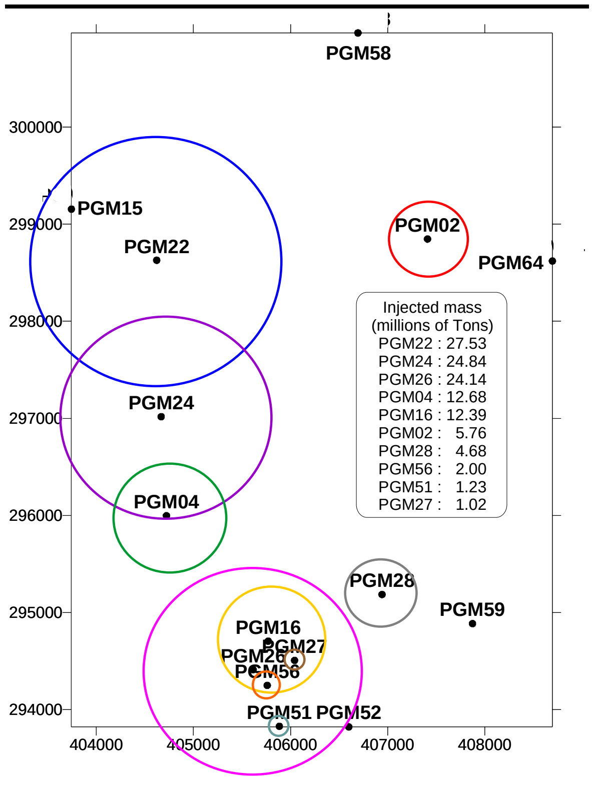

Figure 3: Injection during March 1994 – July 1998.

Figure 8 (Unit 1, 1994–1998) shows that the pressure decline extended along a central band that runs from north to south; the maximum pressure declines occurred around wells PGM-08 (2 bar/year), PGM-14 (1.89 bar/year), and PGM-58 (1.98 bar/year).

It was anticipated at the beginning of the exploitation phase that the fluids in the reservoir would be moving from north to south, following basically the path indicated by the trend of the pressure decline. Since the average pressure decline for this period was 1.56 bar/year, it appeared that the reservoir was capable of supporting the fluid extraction for the units installed at that time, which included Unit 1 (generating about 55-60 MWe) and three wellhead units (generating about 5–15 MWe).

Figure 9 (Units 1 & 2, 1998-2000) indicates that the major pressure decline in this period was concentrated around PGM-09, PGM-14, PGM-23 and PGM-58, where the main production zone of the field is located. The monitoring data indicate decline rates close to 2.1 bar/year, which are higher than the average pressure decline obtained during the first period. During this second period, in which the generation level was between 115 and 125 MWe, the pressure decline reached an average value of 1.62 bar/year (similar to the previous period).

In Figure 10 (Units 1, 2 & 3, 2000 – April 04) it can be observed that the pressure decline increased in PGM-09 (2.74 bar/year) and to the south of this well, reaching well PGM-27 to the south and also wells PGM-23 and PGM-25 to the southwest.

This zone of pressure drawdown is consistent with the results of the numerical simulations carried out, which locate the same area as the principal production zone of the reservoir.

During this period, generation ranged from 142 MWe to 156 MWe. The magnitude of the average pressure decline in all wells monitored during this period was close to 1.75 bar/year.

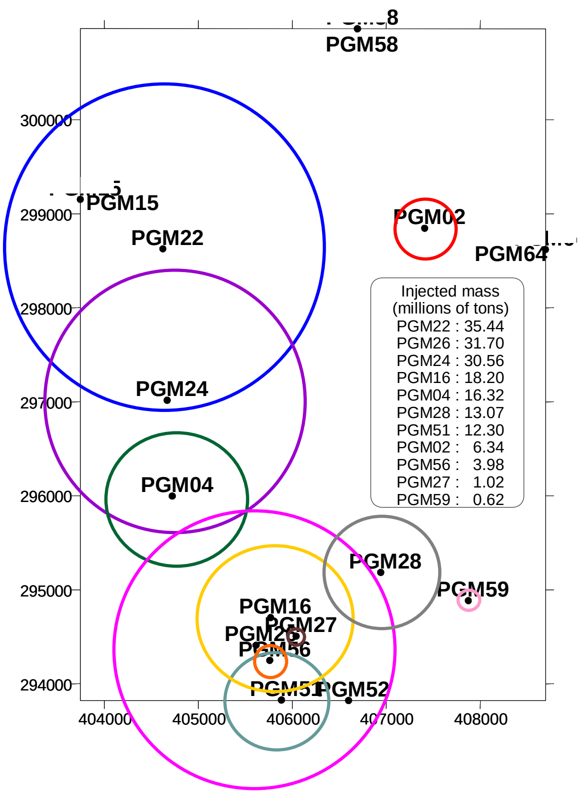

Figure 4: Injection during March 1994 – February 2000.

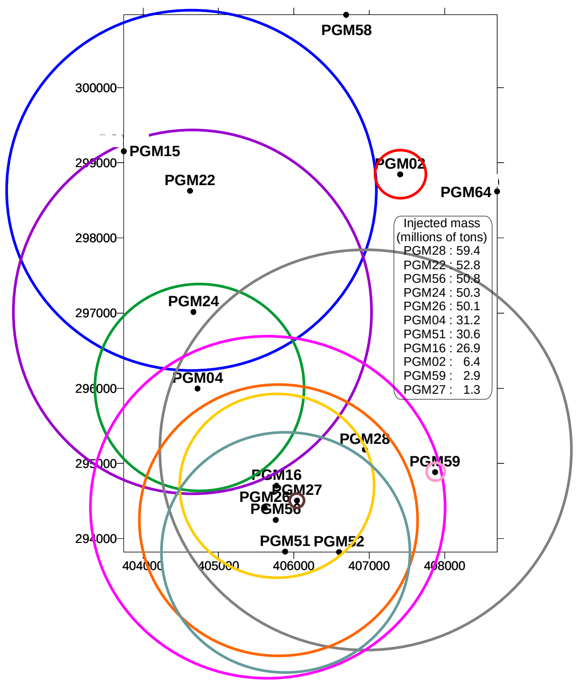

Figure 5: Injection during March 1994 – June 2004.

As expected, and taking into consideration the information from Figures 8, 9 and 10, the main production zone is the one that demonstrated the largest pressure decline.

6. FINAL REMARKS

The available pressure data (both monitoring data and hydraulic levels) indicate that the reservoir pressure decline rate continues to increase as new units come on line. The total pressure decline in the reservoir since production began more than 10 years ago amounts to 20 bars. The water injected in the reservoir has provided pressure support, keeping the pressure decline as low as possible.

Observation periods were defined to identify the incremental contribution to the pressure decline as new units came on line.

The average pressure decline rates estimated for the three periods indicate that the commissioning of Unit 2 increased the average pressure decline rate by about 0.06 bar/year, and the start-up of Unit 3 increased it by 0.13 bar/year.

The pressure decline rate stabilized at around 1.75 bar/year after Unit 3 was commissioned. The zone of pressure decline has expanded since production began, but so far the reservoir has been able to support the current rate of fluid extraction.

The latest pressure decline rates in the reservoir as shown in Figure 10 suggest that injection should be increased in wells PGM-25 (to the west), and PGM-33 and PGM-35 (to the south), in order to minimize the pressure drawdown in the production zone, provided that the additional injection load will not cool the production zone excessively.

An injection line to PGM-33 is already under construction and should be ready by the end of 2004. Next year the design of another line to PGM-25 will be completed. Injection into PGM-35 is programmed to commence when the wellhead unit is moved to PGM-29, an event which is expected to take place in early 2006.

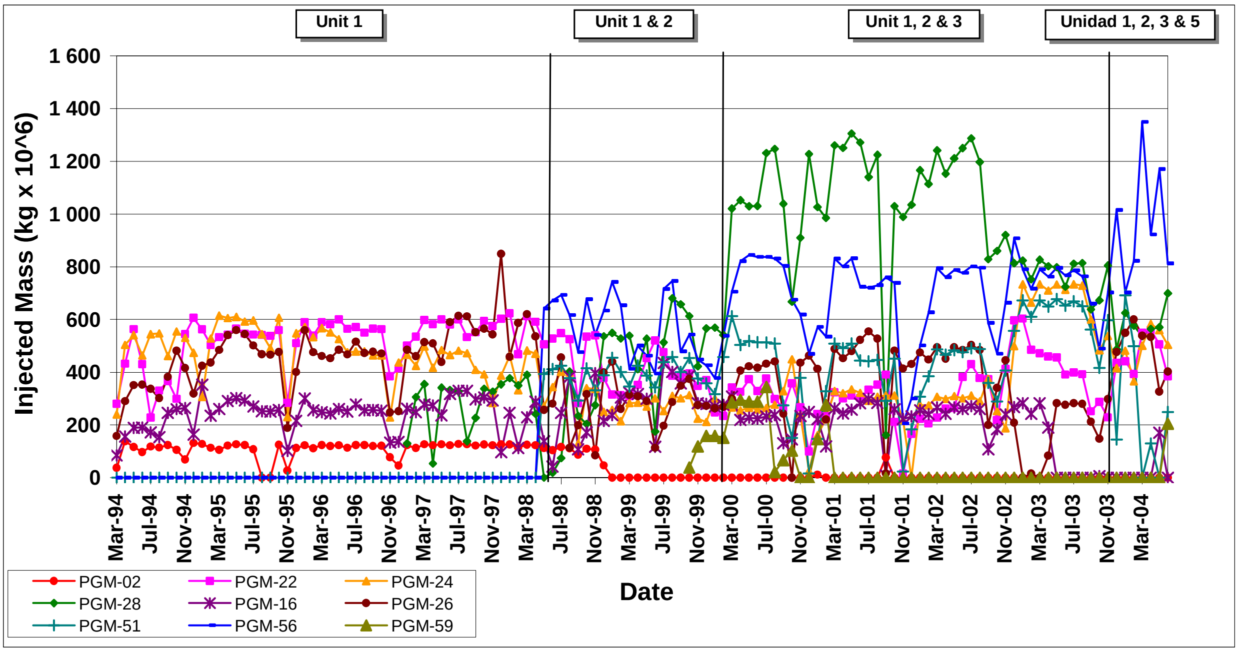

Figure 6: Brine Injection History of the Injection Wells (March 1994 – June 2004).

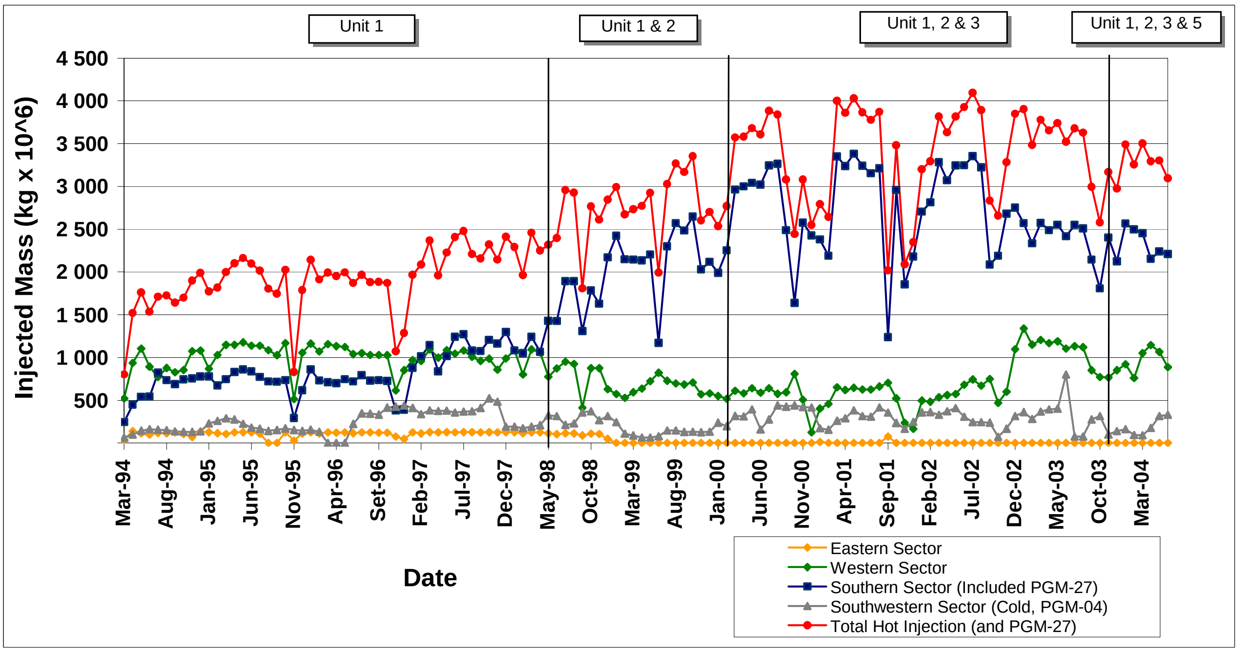

Figure 7: Injection in the Different Sectors of the Reservoir (March 1994 – June 2004).

Table 2: Observed Pressure Declines in Geothermal Wells.

Well	Use	Period 1 March 1994 – July 1998 Unit 1			Period 2 August 1998 – February 2000 Units 1 & 2			Period 3 March 2000 – April 2004 Units 1, 2 & 3		
		Measured Pressure (bar/year)	Hydraulic Levels (bar/year)	Average (bar/year)	Measured Pressure (bar/year)	Hydraulic Levels (bar/year)	Average (bar/year)	Measured Pressure (bar/year)	Hydraulic Levels (bar/year)	Average (bar/year)
PGM-08	P	1,91	2,11	*2,01*						
PGM-09	O	1,43	1,93	*1,68*	1,91		*1,91*	2,74		*2,74*
PGM-14	P		1,89	*1,89*	2,18		*2,18*			
PGM-15	O		0,92	*0,92*	1,33	1,15	*1,24*		1,51	*1,51*
PGM-19	P		1,22	*1,22*		1,54	*1,54*			
PGM-23	O					2,17	*2,17*		1,83	*1,83*
PGM-25	O		1,74	*1,74*		1,77	*1,77*	2,46		*2,46*
PGM-27	I		1,60	*1,60*		1,14	*1,14*		1,94	*1,94*
PGM-28	I	1,60		*1,60*						
PGM-35	O								0,71	*0,71*
PGM-38	O								1,13	*1,13*
PGM-42	P		1,51	*1,51*						
PGM-47	P	1,90	1,52	*1,71*		1,58	*1,58*			
PGM-49	P		1,47	*1,47*						
PGM-52	I	1,52		*1,52*						
PGM-58	O		1,98	*1,98*		2,14	*2,14*		2,14	*2,14*
PGM-59	O	1,02		*1,02*		0,49	*0,49*		1,30	*1,30*
PGM-64	O								1,71	*1,71*
Average		***1,56***	***1,63***	***1,56***	***1,81***	***1,50***	***1,62***	***2,60***	***1,53***	***1,75***

Note: P = Production Well, I = Injection Well, O = Observation Well

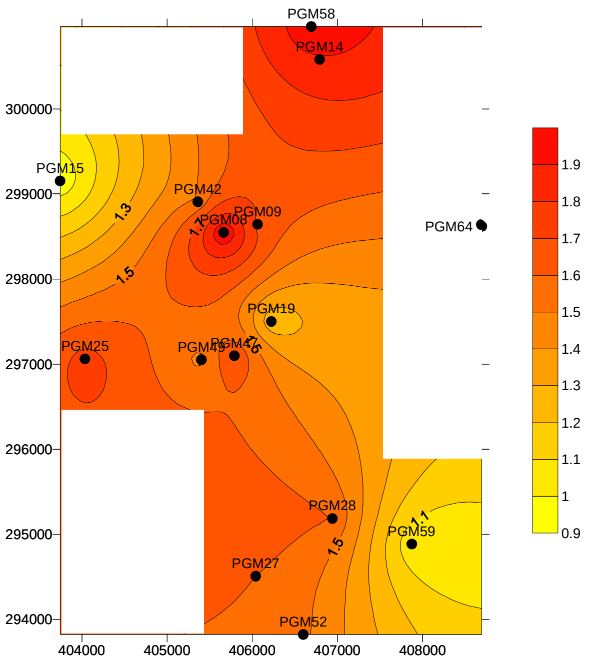

Figure 8: Pressure Decline during March 1994 – July 1998.

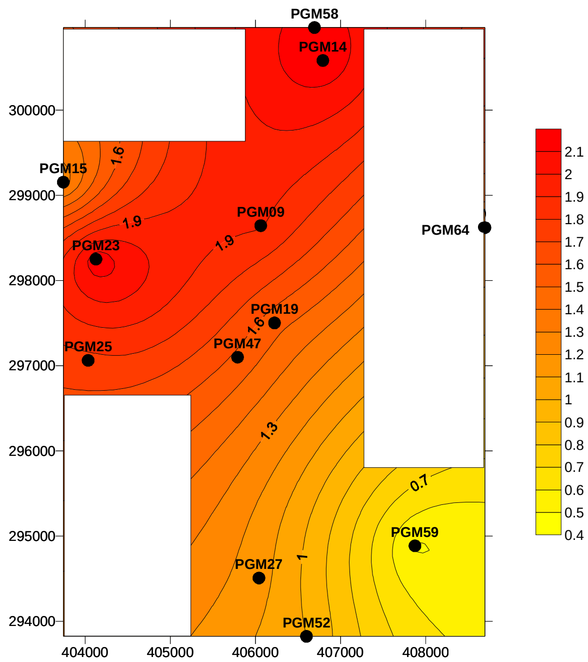

Figure 9: Pressure Decline during June 1998 – February 2000.

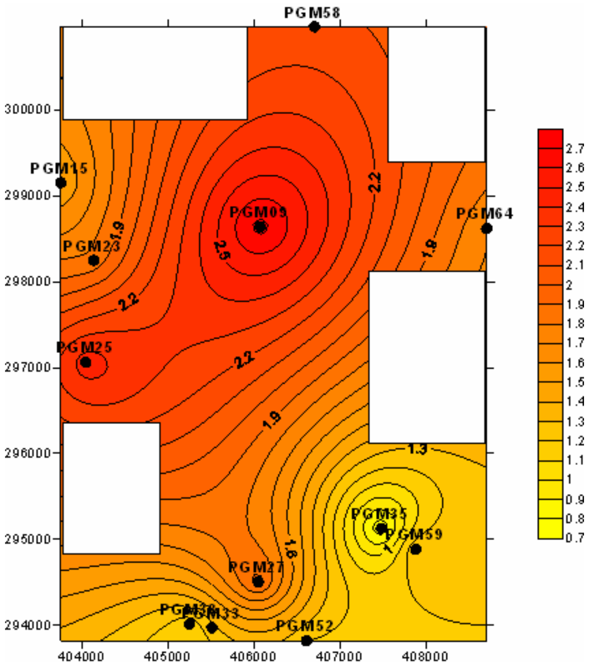

Figure 10: Pressure Decline during March 2000 – April 2004.

ACKNOWLEDGEMENTS

The authors thank Roger Henneberger (GeothermEx, Inc.) for editing and improving the manuscript.

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