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Reservoir Pressure Behavior during Fourteen Years of Exploitation in the Miravalles Geothermal Field, Costa Rica (1994-2008)

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ABSTRACT

The Miravalles geothermal field has a liquid dominated two phase reservoir with temperatures of 220-250ºC. Miravalles started to operate in March 1994 with a 55 MWe power plant; nowadays, it produces a maximum of 155 MWe, using three condensing units (136 MWe), one back-pressure unit (5 MWe) and a binary plant (14 MWe). This production represents approximately a 12% of the total energy consumption of the country.

This report includes an analysis of the data related to reservoir pressure decline obtained by three different methods. Data were obtained from pressure monitoring in observation wells, measurement of hydraulic levels and from the static pressure profiles in productive and inactive wells. In order to do an analysis of the reservoir behavior during the fourteen years of exploitation, pressure data were correlated with information about extracted and injected mass.

Data analysis shows a wide range of pressure decreases, the drops varies from 1-2 bar/year in the production areas and from 0.5-1.2 bar/year in the injection and peripheral zones. These values are lower than those obtained during first 10 years of exploitation. Some factors related to this behavior are**:** the changes in the mass extracted and injected in the reservoir during the power plants stops, the variation produced by the management of the wells to avoid an over exploitation of the reservoir, and finally the increase in the number of wells that produce two-phase fluids. The pressure behavior confirmed a good connection between the different permeable zones found in the reservoir.

1. INTRODUCTION

Costa Rica is located in the southern part of Central America. The Miravalles geothermal field is located on the southern flank of the Miravalles volcano in the northwest zone of the country. The first geoscientific studies conducted in Miravalles started in the mid 70`s, and to date 53 deep wells have been drilled, including production, injection, observation and dry wells (**Figure** 1).

The Miravalles geothermal field is a liquid dominated-two phase reservoir, with temperatures between 220-250ºC with a drilled reservoir thickness at least of 1000 m. The first power plant (55 MWe) in Miravalles, was inaugurated in March 1994, with the second unit (55 MWe) commissioned in September 1998. An additional 5MWe back pressure unit located in the central part of the field started production in 1996. In February 2000, ICE joined to a private company, "Geoenergía de Guanacaste", to build the third unit with 27 MWe of capacity under a BOT modality (Build-Operate-Transfer).

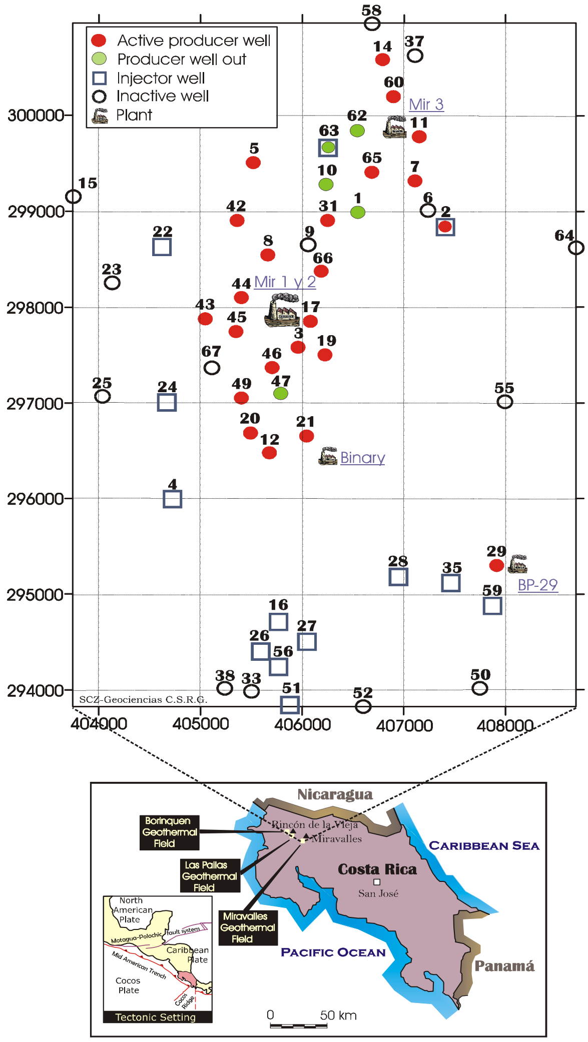

Figure 1: Costa Rica borders, tectonic setting and location of the wells in the Miravalles Geothermal Field (Modified from Chavarría, 2003).

ICE carried out different tests on available wells to define the reservoir pressure drop, which could affect the production behavior. Three methods were used to obtain information about the reservoir pressure behavior. A briefly description of each one is presented:

- Direct measurement: the pressure was measured in observation wells using electronic equipment, including quartz pressure transducer, data logger and the pressure chamber. The measurements were taken in eleven wells at different periods. Since January 2008, measured data has suffered larger variation, and these values are not used in this analysis.

- Hydraulic levels: measurements were taken in observation and inactive wells once a month.
- Static pressure and temperature measurements in available production wells during the scheduled preventive maintenance (shutdowns) of the power plants. Measurements were also conducted once a year in observation and inactive wells.

The information obtained was correlated with the extracted and injected mass, in order to establish the effects produced in the reservoir by the exploitation strategy.

2. DATA EXAMINATION

2.1 Hydraulic Levels

Figure 2 shows data obtained from hydraulic water levels measured in 22 inactive and observation wells through the time. The initial date corresponds with the beginning of exploitation in March 20, 1994. The commissioning dates of the second unit (June 1998) and the third unit (February 2000) are also highlighted in the figure. Also included at the end of 2002 is another division related to the reduction in mass extracted of the reservoir and with the increase in the injected water in the south and with the corresponding reduction in the west part of the field.

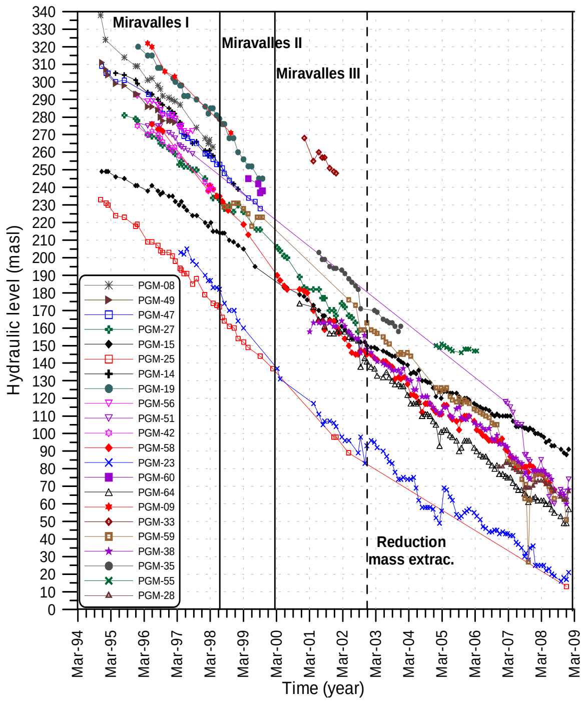

Figure 2: Hydraulic levels measured in Miravalles wells.

Data analysis indicates an average decrease of 210 m (approximately 21 bar), in the hydraulic levels during the fourteen years of exploitation. It may be noted that water levels depend on the location of wells in the geothermal field. Also it is noticeable that the trend is continuing over the time.

2.2 Continuous Pressure Monitoring

The pressure monitoring started in August 1994 and concluded in December 2008. Pressure was measured in eleven wells located in different sectors of the field. **Figure** 4 shows the pressure decline trend together with the average mass extracted and injected in Miravalles. Also included is the sequence of operation of the different power plants. The reservoir pressure gradually declined since the beginning of exploitation and varied considerably in response to changes in mass extraction.

Data analysis shows that variations in mass extraction and injection in some specific areas of the field produced pressure changes in some wells, affecting the general behavior of the pressure trend for each well.

In general terms, data indicate an increase in the pressure drop from the first period to the third one, while in the fourth period, pressure decline was reduced considerably due to-the reduction in the mass extracted from the reservoir and the presence of a vapor cap in several productive wells.

2.3 Pressure Decline Obtained from Static Profiles

Static temperature and pressure profiles were taken in the observation and inactive wells once or twice a year. Also, during plant shutdowns, static profiles were carried out in the productive wells. Using these data, it is possible to estimate the pressure decline in the different sectors of the field. **Figure** 3 shows a sample carried out with data collected in well PGM-31.

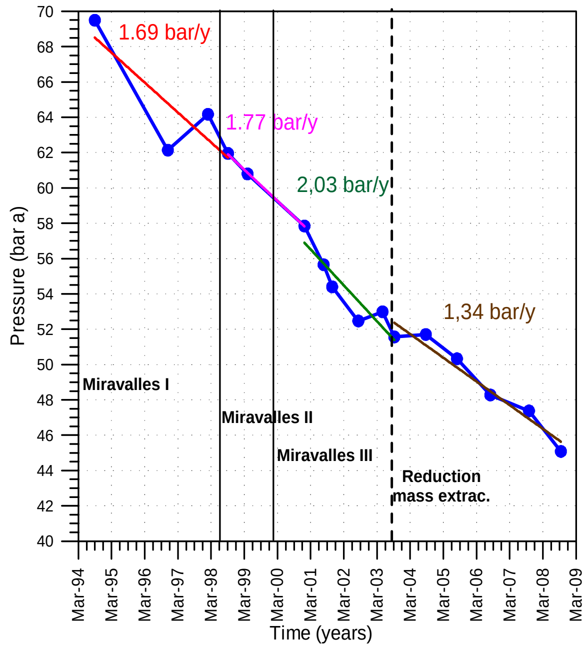

Figure 3: Evolution of static pressure in PGM-31.

2.4 Results

Table 1 shows the pressure decline values obtained from the three methods mentioned above. Also included are the wells' utilization and the calculated average pressure decline for each period. It should be noted that it was not possible to determine the average pressure decline for each well, because data were insufficient or anomalous in several cases.

In general, it can be seen that there was considerable variation in the measured pressure decline according to the method used. The difference confirms the value of obtaining pressure data from different methods to reduce the uncertainty of the value estimation.

2.5 Pressure Decrease Trend by Period

Data were analyzed with the computer software SURFER, to obtain a two dimensional interpretation for the pressure decline defined for each period.

The average pressure decrease obtained for each well by period was plotted, and the analysis permits to define the reservoir zones more affected by the exploitation. All figures include the 2 bar/year drop pressure line (dotted) to facilitate the visualization of pressure decrease trend, and in the legend, into the blue rectangle, is remark the variation ranges measured in each map.

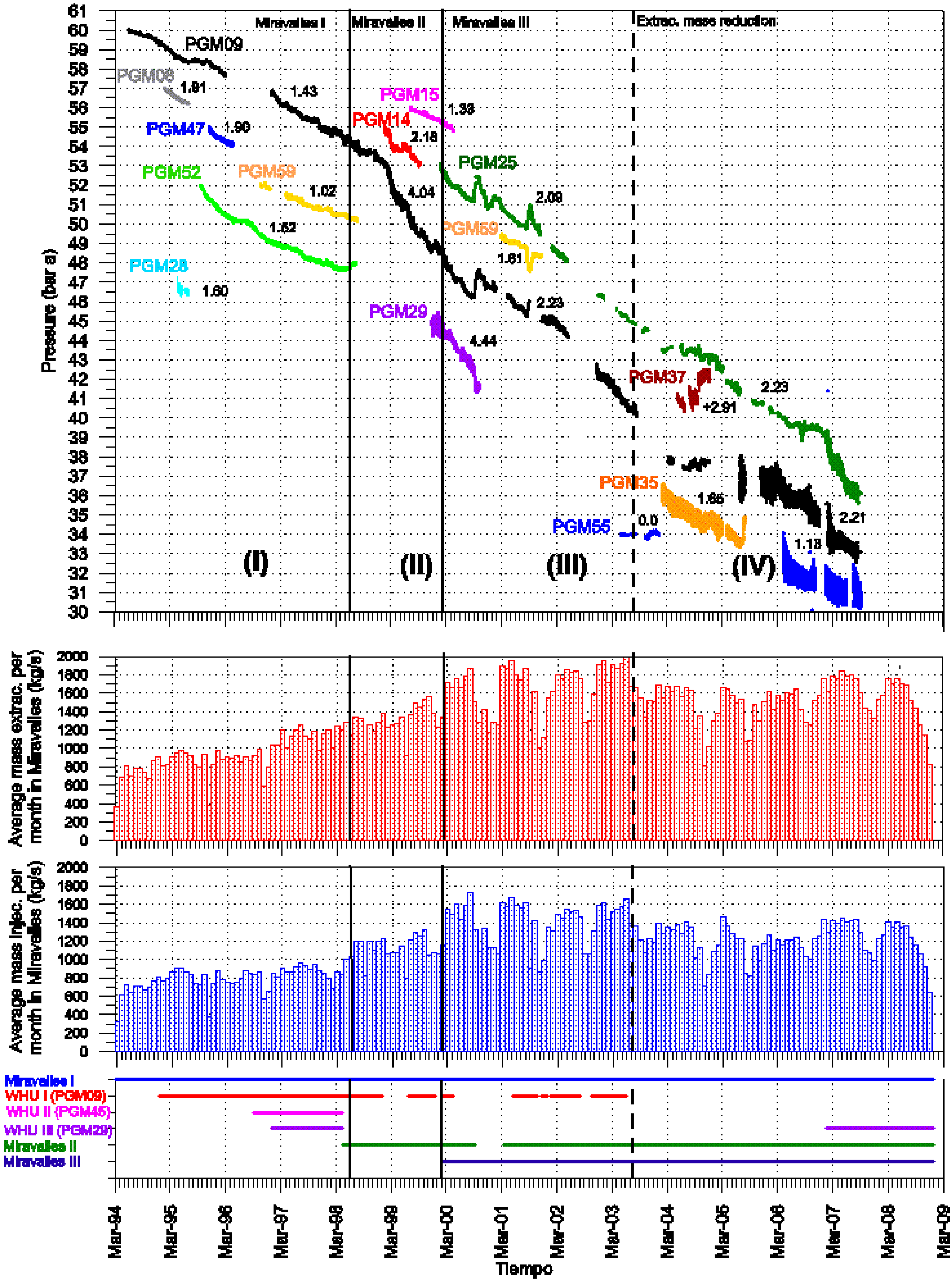

Figure 4: Reservoir pressure decline in the Miravalles wells.

Table 1: Pressure decrease calculated with different methods and for different time periods in the Miravalles wells.

	I Period (Mar98-Jun98) (0-1565) Miravalles I				II Period (Jul98-Feb00) (1565-2173) Miravalles I y II				III Period (Mar00-Ago03) (2173-3420) Miravalles I, II y III				IV Period (Set03-Ene09) (3420-5450) Extracted mass reduct. Miravalles I, II y III			
Well	CPM	HL	SP	*Average*	CPM	HL	SP	*Average*	CPM	HL	SP	*Average*	CPM	HL	SP	*Average*
PGM-01			2.06	***2.06***			2.38	***2.38***			2.09	***2.09***				
PGM-05			1.84	***1.84***			1.51	***1.51***			1.79	***1.79***			0.77	***0.77***
PGM-08	1.91	1.83	1.70	***1.81***			2.05	***2.05***			1.47	***1.47***			0.83	***0.83***
PGM-09	1.43	1.93	1.75	***1.70***	4.04			***4.04***	1.55		2.48	***2.03***	2.21		1.19	***1.70***
PGM-11			1.49	***1.49***			1.78	***1.78***			1.53	***1.53***			1.40	***1.40***
PGM-12			1.58	***1.58***			1.73	***1.73***			1.38	***1.38***			1.54	***1.54***
PGM-14		1.70	2.00	***1.85***	2.18		1.61	***1.90***			1.59	***1.59***			1.33	***1.33***
PGM-15		1.02	0.60	***0.81***	1.33	1.58		***1.46***		1.23	1.71	***1.47***		0.93	1.26	***1.10***
PGM-17			2.31	***2.31***			1.43	***1.43***			1.84	***1.84***			1.38	***1.38***
PGM-19		1.41	1.30	***1.36***		2.63	2.81	***2.72***			2.91	***2.91***			2.40	***2.40***
PGM-20			1.41	***1.41***			1.60	***1.60***			1.82	***1.82***			1.37	***1.37***
PGM-21			1.71	***1.71***			1.61	***1.61***			1.63	***1.63***			1.79	***1.79***
PGM-23		2.00		***2.00***		2.25		***2.25***		1.34	2.20	***1.77***		1.06	1.13	***1.10***
PGM-25		1.63	1.38	***1.51***		1.73	2.28	***2.01***	1.69	2.00	1.80	***1.83***	2.23		1.29	***1.76***
PGM-27		1.13	0.87	***1.00***		1.51	0.88	***1.20***		1.67	2.25	***1.96***			0.36	***0.36***
PGM-28															2.07	***2.07***
PGM-29									4.44		1.88	***3.16***			1.78	***1.78***
PGM-31			1.69	***1.69***			1.77	***1.77***			2.03	***2.03***			1.34	***1.34***
PGM-33										1.77		***1.77***				
PGM-35															1.16	***1.16***
PGM-37							2.36	***2.36***			2.24	***2.24***			1.93	***1.93***
PGM-38										1.07	1.77	***1.42***		1.24	1.42	***1.33***
PGM-42		1.23	3.16	***2.20***			3.76	***3.76***			1.29	***1.29***			1.31	***1.31***
PGM-43															1.36	***1.36***
PGM-44											2.44	***2.44***			1.21	***1.21***
PGM-45			3.65	***3.65***			3.54	***3.54***			3.38	***3.38***				
PGM-46			1.71	***1.71***			2.61	***2.61***			1.63	***1.63***			1.12	***1.12***
PGM-47	1.90	1.52	1.73	***1.72***		1.63	2.22	***1.93***			1.65	***1.65***			1.59	***1.59***
PGM-49		1.42	2.08	***1.75***			1.47	***1.47***			1.65	***1.65***			0.57	***0.57***
PGM-52	1.52		0.65	***1.09***			-0.61	***-0.61***			-0.77	***-0.77***			0.39	***0.39***
PGM-55									2.30	0.22		***1.26***			1.97	***1.97***
PGM-58						2.12	1.86	***1.99***		1.53	1.88	***1.71***		1.17	1.08	***1.13***
PGM-59	1.02			***1.02***		0.79		***0.79***	1.81	1.84		***1.83***		1.74	1.51	***1.63***
PGM-60											2.16	***2.16***			1.55	***1.55***
PGM-62											1.03	***1.03***				
PGM-64										1.57	1.97	***1.77***		1.36	1.86	***1.61***
PGM-66															1.09	***1.09***
Totales	1.56	1.53	1.75	***1.71***	2.52	1.78	1.94	***1.97***	2.36	1.42	1.82	***1.78***		1.25	1.34	***1.36***

PMC: continous pressure monitoring
HL: hydraulic levels
SP: static profiles

2.5.1 Miravalles I: 1994-1998

Figure 5 shows the pressure decline values obtained during this period. The higher values had a NNE-SSO orientation, with the maximum value near to wells PGM-17 and PGM-42 located in the middle of the field. Also, the injection zone to the south showed low-intermediate pressure decline (PGM-27 and PGM-52). The lowest decline occurred in the peripheral zones, represented by wells PGM-15 and PGM-59. Values calculated vary between 0.8 and 2.5 bar/year.

2.5.2 Miravalles II: 1998-2000

Figure 6 shows the pressure decline in the period 1998-2000; the highest decline was registered in the north-center area of the field near to wells PGM-42, PGM-09 and PGM-45. An increase in the pressure decline in the west part of the field is seen, which is probably related to the reduction in injection in this zone during this period. In the main injection zone, located in the south, the pressure continued declining. Nevertheless, the mass injected in this sector had an important increase. The lowest decline is located in the south-east part of the field, where PGM-52 and PGM-59 are located. Drop pressure varies from 0.2 and 4.2 bar/year.

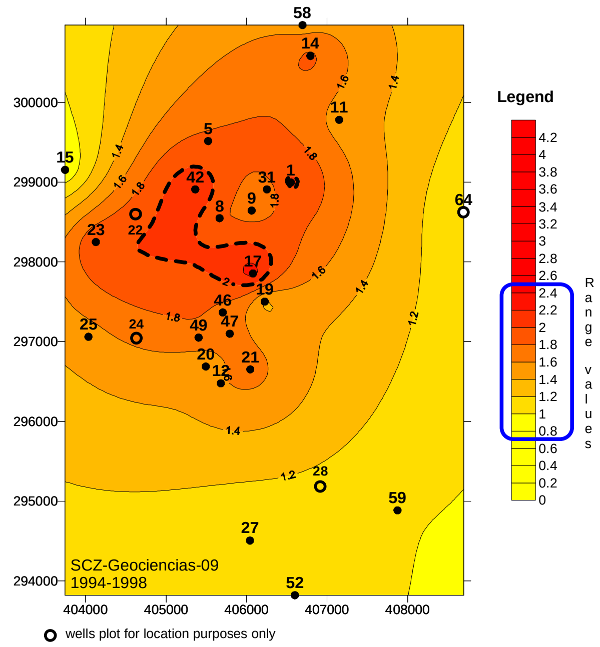

Figure 5: Pressure decline in the period 1994-1998.

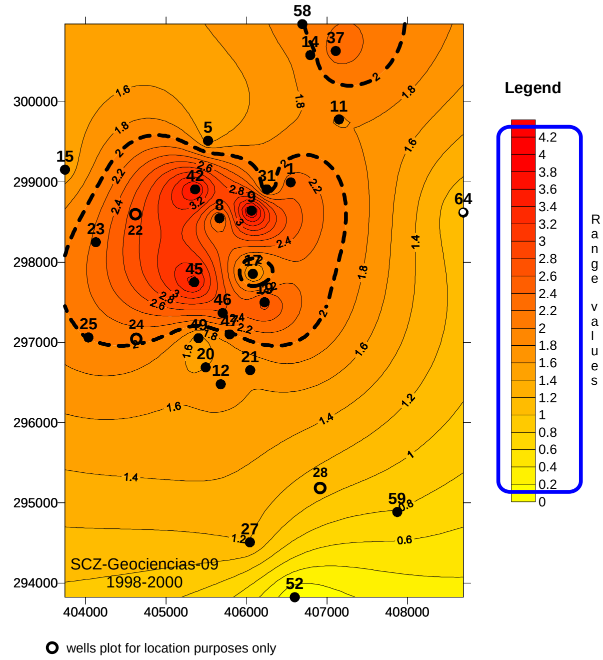

Figure 6: Pressure decline in the period 1998-2000.

2.5.3 Miravalles III: 2000-2003

Figure 7 shows the pressure decline during this period; values indicate a reduction of the maximum decline pressure compared with the second period, but an increase with respect the first period. The highest pressure decline is located in the central area near to wells PGM-45 and PGM-19, but there were also zones with higher drops to the north (PGM-37 and PGM-60) and south-east (PGM-59 and PGM-27). These conditions indicate an enlargement in the pressure zone affected by the reservoir exploitation, but a reduction in the maximum value of pressure drop. The lowest pressure decline was again located to the peripheral wells (PGM-52, PGM-55 and PGM-15).

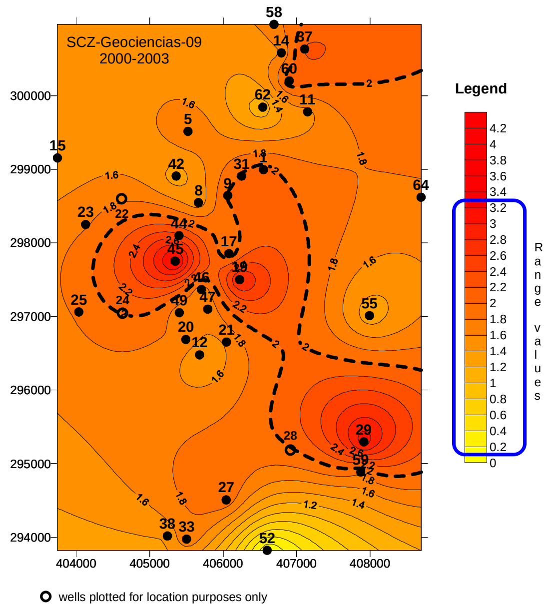

Figure 7: Pressure decline in the period 2000-2003.

2.5.4 Reduction of Mass Extracted: 2003-2008

Figure 8 shows an important change in the pressure behavior with respect to previous periods. Changes could be related to several changes in the last six years:

- Due to the lost of fourth producer wells at the north-center part of the field, the total mass extracted in the reservoir, was notably reduced since 2003.
- In order to try to improve the hydrodynamic in the reservoir some changes in the injection strategy were made. The main change was to use the wells located near the PGM-27 for injection, and PGM-28 was no longer used as the main injection well of the field.
- Finally, injection wells from the west part (PGM-22 and PGM-24), injected less waste fluids. This is because the Fifth Unit of Miravalles (Binary Plant) was brought online in 2005.

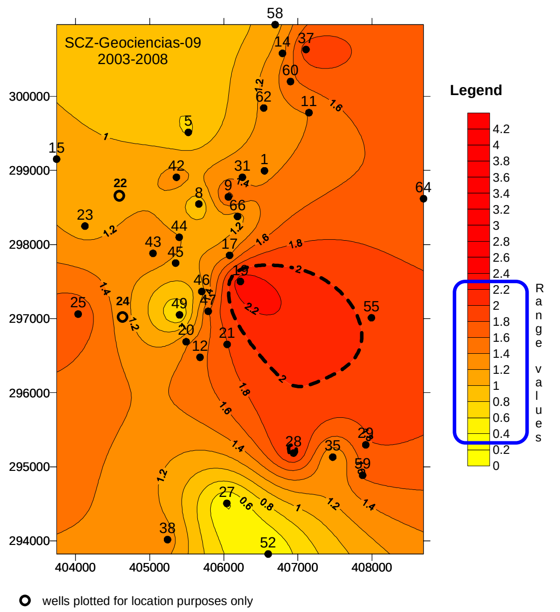

Figure 8: Pressure decline in the period 2003-2008.

The higher pressure drop has a north-south trend with the highest value in the east sector, particularly in the PGM-19. Wells with lower pressure drops correspond with injection wells (PGM-27, PGM-35), and in other cases, wells are located near injection wells (PGM-49 to PGM-24 and PGM-05 to PGM-22). The situation with PGM-25 is not clear because it has a relatively high pressure drop, but is out of the main productive zone.

3. CONCLUSIONS

Data obtained from continuous monitoring of pressure, hydraulic water levels, and static pressure profiles showed a significant response to the extracted and injected mass in the field, indicating the importance of use these tools to estimate the reservoir pressure decline.

As discussed previously, and related with data include in the **Table** 1, the Miravalles productive history could be divided into four periods. During the first period, the pressure decline was 1.71 bar/year. Later when the second unit started operation in 1998, the pressure drop increased to 1.97 bar/year. With the incorporation of the third unit in the year 2000, a reduction in the pressure decline to 1.78 bar/year was observed; finally, since 2003, when the mass extraction was reduced, the pressure drop was notably reduced to 1.36 bar/year. A possible explanation to the behaviour observed, suggests that the first change, in 1998, was consequence of an increase (approximately 40%) in the mass extraction of the field; while in the year 2000, the change could be related with the presence of several wells producing in two phases, mainly in the north part of the field, causing the reduction in the extracted liquid mass. Finally in 2003, the reduction in the mass removed as a result of sustainable management of the reservoir and the general increase in the fluid enthalpy produced a notable reduction in the pressure drop. It is also possible that changes in injection policies made since 2003 have affected the pressure trend.

The pressure contour maps show that the location of greatest pressure decline has been changing. Initially it was in the central zone. Recently it expanded to the north and south sectors, and finally, is located in the east zone of the field. The tendency confirms that the zones most affected zone by exploitation are associated with the productive wells. Also it could be seen that magnitude of pressure decline started to stabilize in time; although an expansion of the area affected by the pressure decline is evident under continued exploitation.

The Miravalles reservoir has shown a fast response to mass flux variations related to plants shutdowns, confirming that, in general, the wells have a good hydraulic interconnection. Detailed analysis in some wells indicate that a reduction of 30% in mass extracted or injected generated a change of approximately one bar in one month. After the shutdown, the pressure drop required approximately two months to return to the former trend observed (Castro, 2005).

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