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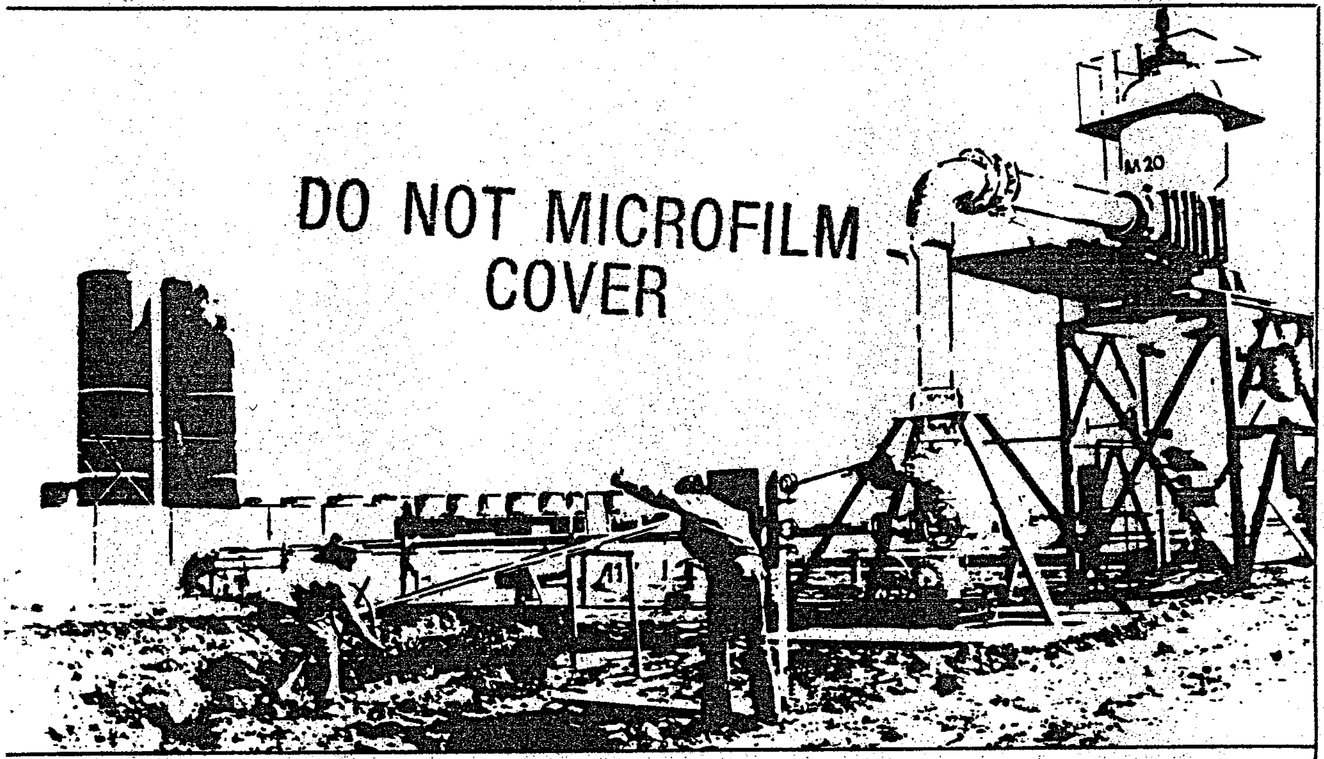

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PRODUCTION CHARACTERISTICS OF SOME CERRO PRIETO WELLS

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INTRODUCTION

The Cerro Prieto geothermal field, located about 35 km south of the U.S.-Mexican border, has been producing electrical power from a large underlying geothermal reservoir since March 1973. An initial capacity of 75 MWe was obtained in February 1974 when a total of 12 wells were used for steam production. In April 1979, a total of 26 wells supplied steam to produce 150 MW of electric power. Presently, the field is producing about 180 MWe, including 30 MWe produced by a secondary flash system.

During its 9 years of fluid production, the field has undergone various changes, such as pressure drawdowns, reservoir flashing, decline in well production rates, and decline in the average enthalpy of the produced fluid (Goyal et al. 1981). Furthermore, some wells have exhibited peculiar behavior such as production of almost dry steam and increasing well head pressures and mass production rates. It is also observed that production characteristics of some wells change as a result of the opening of a new production well in their vicinity. For example, an increase in enthalpy and decline in the production rate is observed in nearby wells due to a reduction in reservoir pressure created by the new production well. Thus, it is useful to study these wells to find how the field is reacting to fluid production. It is also useful to study the distributions of heat and mass in the field and their changing patterns due to production. We can also study which part of the field is becoming hotter or colder due to its exploitation, in which directions the hot and cold waters are flowing, and whether or not the α and β aquifers are in hydraulic communication with each other.

This kind of study is very important to both the modeler and the field engineer. A modeler can use the information generated by this study to construct and validate a model that predicts the field's future behavior under various production and injection schemes. The field engineer will gain a better overall understanding of the behavior of the field, greatly enhancing his ability to make day to day decisions. Finally, this study will further our knowledge of production mechanisms in the Cerro Prieto geothermal field. Comparison with studies of other geothermal fields will provide a valuable opportunity to identify and characterize certain common fluid production features.

This analysis is mainly based on wellhead production data from the Cerro Prieto geothermal field. The wellhead data for this field, which include wellhead pressure, separator pressure, and water and steam flow rates, are recorded monthly for each well. This information enables the calculation of the dryness fraction and the enthalpy of the produced fluid under separator conditions. Interpretation of the results take into account the geologic model of Cerro Prieto developed by Halfman et al. (1982, this volume).

DISTRIBUTION OF HEAT AND MASS PRODUCTION IN THE FIELD

To determine the areal distribution of heat and mass production in the field and its changing patterns with time, we have used the set of geometric symbols shown in Figure 1. The circles, squares and triangles represent total flow rates of steam-water mixture ($\dot{M}$) less than or equal to 100, between 100-200, and greater than or equal to 200 t/h, respectively.* Thus, they indicate mediocre, good, and very good production wells, respectively. These limits are arbitrarily chosen from the production data of numerous wells in the field.

The shading of the geometric figures is used to represent the enthalpy of the produced fluid. Unshaded, half-shaded and fully-shaded figures represent enthalpies of less than or equal to 275, between 275-350, and greater than or equal to 350 kcal/kg, respectively. These

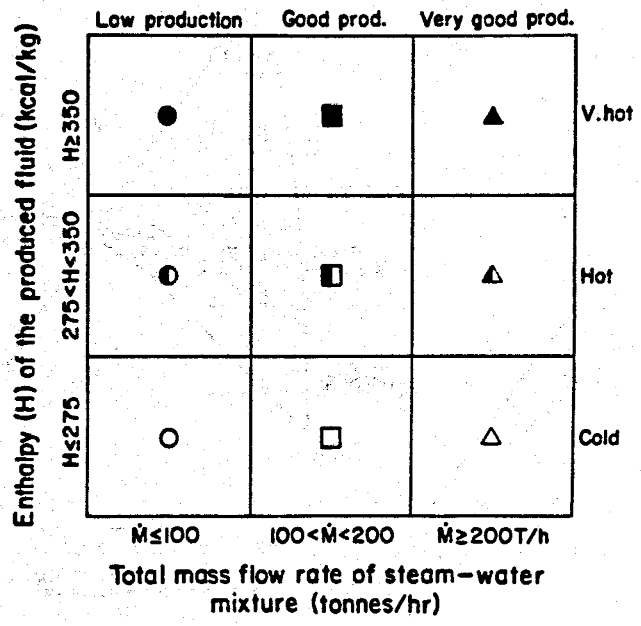

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Figure 1. Symbols used to represent heat and mass production rates in Cerro Prieto wells.

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* t/h = metric tons per hour

limits are again arbitrarily chosen. However, downhole calculations using a wellbore model (Goyal et al., 1980) show that fluid with an enthalpy less than 275 kcal/kg tends to be single-phase at the bottom of the well. The different shadings indicate cool, hot, and very hot wells, respectively.

Initial Reservoir Condition

Figure 2 shows the distribution of fluid enthalpy and mass flux in the field as of December 1973. Faults identified from the well logs are also shown in this figure. A total of 11 wells (M-5, M-8, M-9, M-11, M-20, M-26, M-29, M-30, M-31, M-34 and M-39) were producing at that time. The exploitation of Cerro Prieto started only nine months before, in March 1973, with four production wells (M-5, M-9, M-11, and M-29). Thus, the distribution of enthalpy and mass flux shown in this figure could be assumed to represent the initial state of the field. All wells, except for M-26 and M-34, initially produced more than 200 t/h. Thus, the circles and squares of Figure 2 indicate a decline in production with time for most of the wells. It may be noted that wells M-9, M-29 and M-34 on the western side of the field were cold initially and indicate the location of a cold boundary. On the other hand, well M-39 on the north-eastern side was also a cold well. Each well, except these four cold wells, produced fluids with enthalpies between 275 and 350 kcal/kg. This indicates that the wells were not producing very hot fluids initially.

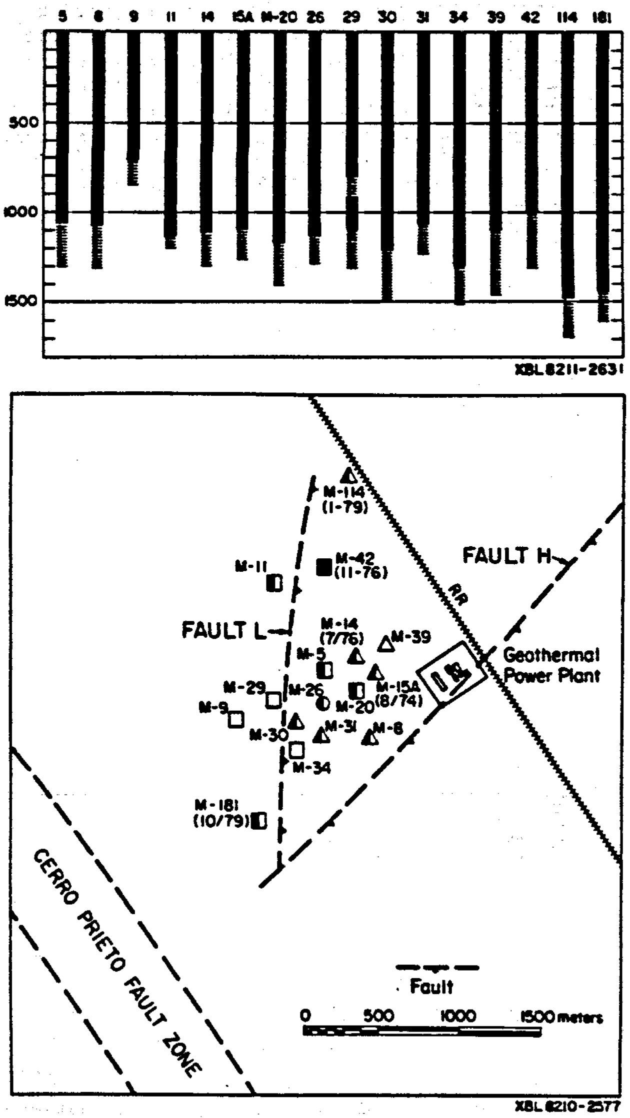

Figure 2. Distribution of heat and mass flux in the Cerro Prieto field as of December 1973.

Wells M-14, M-15A, M-42, M-114 and M-181 shown in Figure 2, did not produce until the date indicated within brackets. The initial mass production from each of these five wells is greater than or equal to 200 t/h. Initial fluid enthalpies for wells M-114 and M-181 were about 285 and 295 kcal/kg, respectively. These wells are closer to the cold northeast and southwest boundaries of the field. The rest of the wells (M-14, M-15A and M-42) were initially either hot or very hot wells, as shown in this figure. The depth intervals from which these sixteen wells were producing are also shown in Figure 2.

Except for wells M-114 and M-181, which produce from the β aquifer (1500-2000 m deep) the rest of the wells draw their fluids from the α aquifer (1200-1500 m deep). Note that wells M-9, M-29 and M-31 have completed intervals above 1200 m depth. In summary, this figure describes the initial state of the field for both α and β aquifers. Both aquifers in this area are hot and there is evidence that the α aquifer has cold boundaries to the southwest and northeast.

Reservoir After 7 Years of Production

Figure 3 shows the heat and mass flux distribution in the field as of December 1979, after about 7 years of production. At this time, 27 wells were supplying steam to the power plant. A comparison between Figures 2 and 3 shows that: (i) 19 new production wells were added between December 1973 and December 1979, (ii) some of the 1973 production wells had been taken out of line by 1979, and (iii) all the 1973 wells except cold wells M-9, M-34 and M-39 continued to produce.

Wells M-53, M-84, M-91, M-102, M-103, M-105, M-114, M-130 and M-181 were completed in the β aquifer. The rest of the wells in Figure 3 were completed in the α aquifer.

Some of the wells drilled to the southeast of Fault H produced very hot fluids at very high rates initially. All the wells drilled in the β aquifer, except M-114, M-130, and M-181, produce very hot fluids. This indicates that either the β aquifer is very hot in this region or that the fractured zone is acting as a conduit for upwelling hot waters. The β aquifer, penetrated by wells M-181, M-114 and M-130, is relatively cold, indicating that these wells are located near the thermal boundaries of the field.

well M-29 since August 1979. Wells M-8, M-11, M-20, M-21A and M-31 were shut in temporarily, probably due to low production.

As stated earlier in this paper, a reduction in enthalpy of the produced fluid can be caused by the propagation of a cold front in the same aquifer, draw-in of colder waters from the upper strata, or both, depending upon the location of the well in the field. On the other hand, a decline in the production rate of a well can be caused by scaling in the wellbore, reduced recharge to the aquifer, high resistance to flow due to silica precipitation in the reservoir pores, and/or relative permeability effects in the two-phase region near the well. Some or all of these factors might be contributing to reduced production from the wells.

Rise in Fluid Enthalpy

The reaction of most wells to the continuous exploitation of the field was to produce lower enthalpy fluids at lower rates. However, the behavior of some wells was remarkably different. For example, although the production rates of wells M-20, M-45, M-51, M-84 and M-105 declined over the years, their fluid enthalpies increased.

The heat and mass production of the intermittently produced well M-20 changed from about 280 t/h and 306 kcal/kg in August 1973 to 24.5 t/h and 371 kcal/kg in September 1978 when it was taken out of production. It was reopened in October 1979, but the production rate continued to decline while the enthalpy continued to rise. Well M-45 produced 60 t/h and 433 kcal/kg in August 1977 compared to 29.5 t/h and 548 kcal/kg in September 1980. Well M-51 produced 308 t/h and 355 kcal/kg in January 1979 compared to 198 t/h and 367 kcal/kg in September 1980. The production from M-84 was 177 t/h and 426 kcal/kg in March 1979 compared to 97 t/h and 482 kcal/kg in September 1980. Well M-105 produced 265 t/h and 354 kcal/kg in December 1978 and 141 t/h and 415 kcal/kg in September 1980.

A continuous increase in enthalpy appears to be related to the declining pressures around a production well due to low recharge. A reduction in pressure results in lower saturation temperatures of a two-phase zone around the well. The lower fluid temperatures set up a temperature gradient between the fluid and the surrounding rock, allowing heat to flow from the rocks to the fluid, thus increasing the fluid enthalpy. These phenomena seem to occur in all five wells mentioned above. If recharge to these wells does not increase, due to seismic activity or otherwise, then these wells may be taken out of the production line or their fluid output combined with that of a better producing well. The lower producing wells M-45 and M-8 were connected to well E-1 in August 1981 and October 1981 respectively, and well M-20 was connected to well E-3 in August 1981.

Flow Barriers

Figure 3 also shows flow barriers inferred on the basis of enthalpy interference data as discussed later in this paper. A solid line indicates that almost no flow occurs between the wells whereas a dashed line signifies a slight amount of flow between them. Analysis of data from wells M-20 and M-45 support the hypothesis relating low recharge and flow barriers: flow barriers around M-20 result in low recharge and a flow barrier located near M-45 reduces recharge from the north.

Some adjacent wells in this field display sharply different characteristics, indicating a heterogeneous/complex system. For example, wells M-114 and M-130, both completed in the β aquifer, show that the aquifer there was initially cool. Over the years, both wells show a reduction in production, with almost no change in fluid enthalpy in M-114 and an increase in enthalpy in M-130. Well M-114 continued to be a cool or nearly cool well, while M-130 is nearly a very hot well. Here again, the small recharge to M-130 may be the cause for the increasing fluid enthalpy. Wells M-34 and M-35 are drilled close to each other and yet they display entirely different characteristics. Well M-34 is a cool and low producer, while M-35 is a hot and very good production well.

In summary, areal distribution of heat and mass flux data suggests that the α and β aquifers are hot and very hot, respectively. The initial cold boundaries of the field were confined to wells M-39 and M-114 in the northeast and to wells M-9, M-29, M-34 and M-181 in the west. In response to large-scale fluid production, the cold boundaries appear to have moved toward the main field, reaching wells M-42, M-14, M-15A and M-21A in the northeast and wells M-30, M-31 and M-26 in the west. Initial production from most wells was very good, with production declining over the years. The enthalpy for most wells in the field also declined. The wells drilled in faulted zones produced very hot fluids at very high rates. The recharge to wells M-20, M-45, M-51, M-84 and M-105 appears to be diminishing. If recharge to these wells does not improve, these wells may be taken out of production as have some other wells in the field.

LOCAL BOILING AND INTERFERENCE BETWEEN WELLS

In the previous section, it was shown that most wells experienced a decline in enthalpy, while some wells experienced a gain in enthalpy. In this section, we shall discuss those wells whose enthalpy fluctuates due to the opening or closing of nearby wells. This is caused by the interference between wells as shown below.

As discussed before, an increase in enthalpy is related to heat transfer from the rocks to the fluid due to a reduction in fluid pressure (and temperature) in a two-phase region. On the other hand, a reverse process is expected to take place if fluid pressure increases. By contrast, in a single phase compressed liquid aquifer, changes in enthalpy due to pressure changes are very small. Since the compressibility of a two-phase fluid is significantly higher than that of a single-phase liquid, the pressure transients are expected to propagate slower in the two-phase reservoir. The

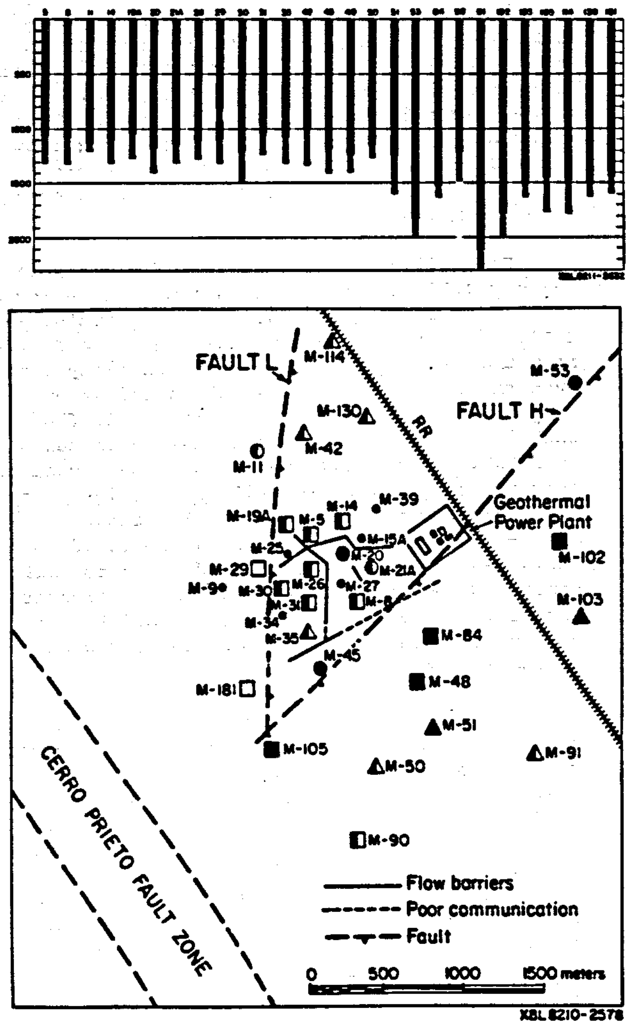

Figure 3. Heat and mass flow rates distributions in the Cerro Prieto field as of December 1979 along with flow barriers shown in Figures 7, 8, 9 and 10.

A decline in mass production rates for most wells in the Cerro Prieto field was observed between 1973 and 1979. M-53 and some of the wells to the southeast of Fault H were supplying steam at good or very good rates as of December 1979. In certain instances production rates increased, (e.g., wells M-8, M-14, M-25 and M-103). An increase in M-8 is attributed to a seismic event which occurred in the summer of 1978. The rise in the other three wells resulted from the installation of smaller diameter production casings, which were decreased from about 8 to 4 inches (CFE Annex Number 6).

Decline in Heat and Mass Production

Aside from an uneven distribution of heat and mass flux in the field, some changes in the production characteristics of wells were also observed. The cold boundaries to the west and northeast appear to move toward the main production area with the exploitation of the field. It was also observed that the fluid enthalpy for most wells in the field declined over the years.

Toward the northeast, wells M-114 and M-39 continued to be cool or near-cool wells. An enthalpy decline was observed in wells M-42, M-14, M-15A and M-21A. Well M-42, continuously producing since November 1976, behaved peculiarly during its first three months of production. Its mass production increased from 190 t/h to 350 t/h and the enthalpy of the produced fluids decreased from 360 to 270 kcal/kg. Thereafter, its enthalpy remained low and its production rate declined continuously.

During continuous production, well M-14 experienced declines in both production rate and enthalpy, from about 205 t/h and 345 kcal/kg in July 1976 to about 155 t/h and 275 kcal/kg in December 1979. M-15A, initially a hot well, produced until it was shut in in January 1977 and then reopened from April to December of 1978. The mass production rate and enthalpy of the produced fluid declined from 300 t/h and 325 kcal/kg in August 1974 to about 60 t/h and 265 kcal/kg in January 1977. This well remained cool and its production rate declined during its second production period in 1978. Well M-21A, initially very hot, showed declines in enthalpy as well as in mass production rate.

Thus, it appears that initially cool or near-cool regions surrounding wells M-114 and M-39 are propagating toward wells M-42, M-14, M-15A and M-21A in response to production. It may be worthwhile to mention here that the influx of relatively cool water from overlying aquifers has also contributed to a decline in the enthalpy of the fluids in the α aquifer (Truesdell et al., 1978; Grant et al., 1981). However, in the northeast, the dominant cooling mechanism appears to be related to the propagation of the cold front. One would expect that for comparable distances relatively larger pressure differences would be needed to draw in waters from overlying aquifers than from the same aquifer if lower permeability intervening layers exist between them. The Cerro Prieto well logs confirm the presence of low permeability shale zones between the α and β aquifers and also between the α aquifer and strata above it (Halfman et al., 1982, this volume).

On the western side of the field, the cool region around wells M-9, M-29, M-34 and M-181 appears to move toward wells M-30, M-31 and M-26 whose enthalpies of about 318 kcal/kg in December 1973, 318 kcal/kg in August 1973, and 322 kcal/kg in August 1973, dropped to about 302, 287 and 288 kcal/kg in December 1979, respectively.

In general, it is observed that the production from most wells is declining. Quite a few wells in the field have been shut in because either the produced fluids were too cool, and/or the production rates were small. Judging by the field data, wells M-9, M-15A, M-34 and M-39 were shut in permanently, apparently for being cold, low producers. In fact, well M-9 has been used as an injection well for untreated brine from rise of enthalpy in a well due to reduced pressure created by a new nearby production well indicates good communication between them.

To study the interference of nearby wells in a production well, a plot of enthalpy and production rate versus time was prepared for well M-8 (Figure 4). In this figure, $\dot{M}$ and H represent mass production rate (in t/h) and fluid enthalpy (in kcal/kg) respectively. Various wells with their initial production dates are also indicated along the time axis. It may be noted that the well is producing very hot or nearly very hot fluids throughout the time period shown in this figure. Initially a very good producer, M-8 showed a declining trend of production rate similar to other wells in the field. Its production rate did increase about four times in the summer of 1978 probably due to a seismic event (CFE annex number 6). Measured enthalpies indicate that this well was either two-phase or close to boiling in June 1973 when it started commercial production. The enthalpy of this well remained almost constant during the first nine months with slight variations in mass flow rate. Well M-31, placed into production in August 1973, did not affect the enthalpy of M-8. However, a small jump in enthalpy and a small reduction in mass flow rate can be seen during the time when well M-35 was put on line in March 1974. A small reduction in mass flow indicated a lower reservoir pressure in M-8. If the fluid in the aquifer is already two-phase a pressure reduction will cause the heat to flow from the rocks to the fluid, increasing the fluid enthalpy as can be seen in Figure 4. However, no such change in enthalpy is expected to occur if the reservoir fluid is compressed liquid. Since M-8 was producing very hot or nearly very hot fluids and showing enthalpy increases, we expect that a two-phase zone exists at least near the well if not far away.

A sharp decline in production rate and a rise in enthalpy was observed in the fall of 1974 when M-21A started production. This shows that the opening of M-21A caused a larger pressure drop in M-8 than that caused by the opening of M-35. The propagation and magnitude of the pressure drop is a function of the distance between wells, formation permeability, kinematic viscosity, and compressibility of the fluid. The pressure drop in M-8 is expected to be larger due to the opening of M-21A than that due to M-35 because it is closer to M-8. However, if we assume that a two-phase zone existed around M-8 even before March 1974, the magnitude of the enthalpy rise or pressure drop suggests better communication between M-8 and M-21A compared to that between M-8 and M-35.

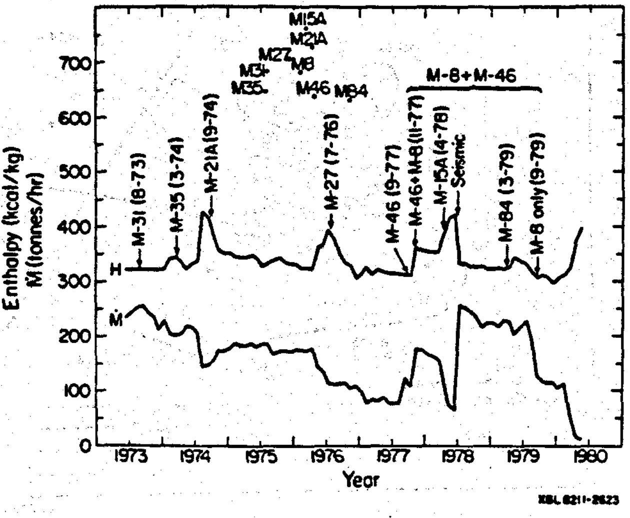

Figure 4. Heat and mass production history of well M-8.

An increase in enthalpy and drop in mass flow rate of M-8 is also observed during the summer of 1976 when well M-27 started production. Since well M-27 is closest to M-8, large pressure drops in the latter are expected. No noticeable changes in either enthalpy or mass flow rate in M-8 can be attributed to the opening of M-46 in September 1977. This probably indicates a poor communication toward the southeast.

It may be noted that the production from M-8 has shown a continuously declining trend over the years (if we neglect temporary humps) with almost constant fluid enthalpy. The increase in production rate and enthalpy, from about 105 t/h and 310 kcal/kg in October 1977 to about 175 t/h and 360 kcal/kg in November 1977, is due to combining the production of wells M-8 and M-46. Both wells used the same separator probably up to August 1979 when M-46 was probably shut in. During this two year period, fluctuations in production rate and enthalpy can be observed. A sharp decline in production and increase in enthalpy can be observed up to June 1978 when seismic activity resulted in lower fluid enthalpies and about four times higher production rate (CFE annex number 6).

Well M-15A, located north of M-8 was produced from April 1978. Around this time an increase in enthalpy and a decline in production flow rate of well M-8 (similar to those related to wells M-35, M-21A and M-27), may be noted. However, at this point, it is difficult to conclude that such a sharp change in flow rate and enthalpy was caused by the opening of M-15A because of its being farther away from M-8. An attempt is made to clarify this point later in this paper.

Well M-84 started production in March 1979. A slight decrease in flow and increase in enthalpy is observed in M-8 about this time. However, these changes are too small for us to arrive at any reasonable conclusions. Moreover, M-84 is far to the southeast of M-8 and any effect is expected to be small. Beyond September 1979, the production rate of M-8 reduced drastically with a corresponding increase in fluid enthalpy. This well was finally shut in for over a year in May 1980 when its production rate dropped to about 14 t/h.

In brief, Figure 4 shows that if the pressure (and temperature) of a two-phase zone surrounding a well is lowered by the opening of nearby wells, it gives rise to an increase in fluid enthalpy due to heat transfer from the rocks and a decline in production rate due to the reduced pressure. One can then qualitatively infer whether the communication between wells is good or poor. In the case of well M-8 it appears that it has good permeabilities toward wells to the north and probably poor ones toward those to the south.

FLOW BARRIERS BETWEEN WELLS AS INTERPRETED FROM WELLHEAD DATA

As discussed in the previous section, an existing producing well may or may not respond to a newly opened producing well depending upon the formation permeability between them. A pressure wave propagates quickly through a high permeability formation, resulting in lower flow rate and higher fluid enthalpy in the already producing well completed in a two-phase reservoir. If, on the other hand, the permeability is low, the pressure interference will be slow. Thus, based on the enthalpy history of nearby wells it is possible to interpret qualitatively whether the permeability between wells is good or poor. The words good communication/poor communication or flow barriers are intended to reflect on the formation permeability between the wells under discussion. Flow barriers between wells can either be natural or man-made. Natural barriers include faults and low permeability zones or layers. Man-made barriers are the ones resulting from fluid production which reduce formation porosity and permeability by mineral precipitation in rocks.

In this section, we attempt to identify these barriers in a gross sense on the basis of enthalpy history only. As discussed in the previous section, an increase in enthalpy is associated with a reduced production rate or lower bottom-hole pressures. These flow barriers are then used to explain the low recharge to some wells shown in Figure 3. It may be emphasized that the interpretation is purely based on enthalpy data and is subject to confirmation.

To determine interference and possible communication barriers between wells, we have divided the main producing field in four different areas, as shown in Figure 5. Only the central part of the field is being considered for this study for the following reasons:

(i) initially wells in this region were either two-phase or close to boiling;

(ii) spacing between wells in this area is small, which increases the possibility of interference between them;

(iii) wells toward the north and west are located on the cool boundaries of the field and the reservoir fluid tends to be liquid water. A small reduction in bottom-hole pressure does not make a significant change in the enthalpy of these single-phase liquid wells. Thus, on the basis of enthalpy data, it is hard to establish flow boundaries for these wells. However, an indication of expanding cold boundaries, as discussed earlier, signifies good communication between these boundary wells.

(iv) The southern-most wells are spaced far apart and were put on line almost at the same time. Both factors make it difficult to obtain the kind of interference data we are looking for.

The plots of water/steam ratio and wellhead pressure versus time were prepared for wells in the different groups up to November 1980 (Figures 6-10). As can be seen in Figure 5, some wells appear in more than one group. The nonproducing wells are also included in these groups. However, the following discussion is confined to production wells only.

Group I

Figure 6 shows a plot of wellhead pressure (WHP) versus time for all the wells in Group I along with their relative positions. The wellhead pressures of M-27, M-35 and M-84 are almost uniform over the years with a slight declining trend. The behavior of M-8 is also almost uniform with a declining trend, except for a small increase in WHP during the first year of production and another increase in July 1978 due to a seismic event (CFE annex number 6).

A sudden rise in WHP of M-21A during the middle of 1978 was caused by a change in the diameter of the production casing from 8 to 2 inches. The excessive sand production and casing damage required the installation of a new casing (CFE annex number 6). Except for a sudden pressure drop in August 1975, the WHP of M-31 is almost uniform with a slight declining trend. The sudden drop in WHP was probably caused by an increase in orifice diameter (personal communication Castillo B.F., 1982). As reflected by these

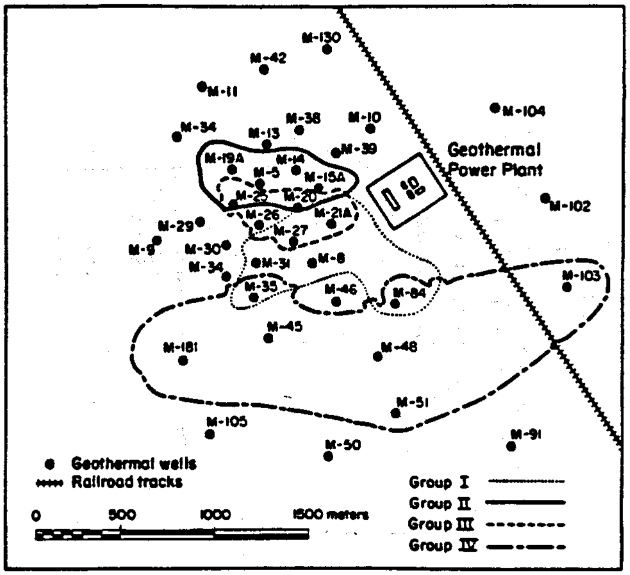

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Figure 5. Well groupings for interference study.

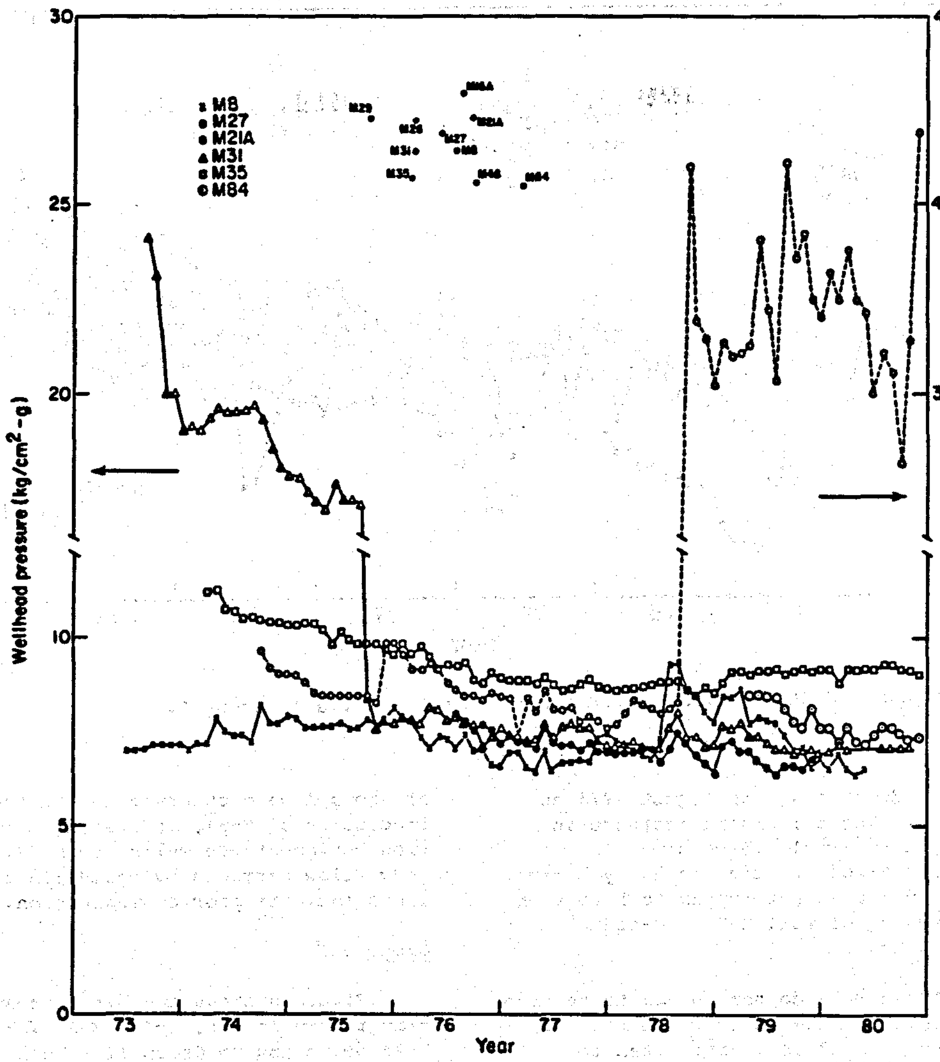

Figure 6. Wellhead pressures versus time for wells in Group I.

wellhead pressures, toward the middle of 1979, all of these wells were fairly good producers with M-35 and M-27 producing at the highest and lowest rates, respectively. It may be noted that the oldest producing well in this group is M-8, which started production in June 1973, followed by M-31 in August 1973, M-35 in March 1974, M-21A in September 1974, M-27 in July 1976 and M-84 in March 1979. Toward the end of 1980 only half of the wells in this group were producing, the rest were shut in probably due to low production.

The water/steam ratio history of the wells in Group I is shown in Figure 7. The wells with lower water/steam ratios indicate higher fluid enthalpy compared to those with higher water/steam ratios. For example, in Group I during 1979-80, well M-84 was the hottest well with highest enthalpy and M-31 was the coldest well. In general, fluid enthalpies show a declining trend with time for most wells except M-84 where an opposite trend can be seen. An enthalpy increase in M-8 may also be observed in mid-1980. As discussed earlier, a decline in enthalpy is caused by mixing with relatively cool waters and an increase can be attributed to local boiling and/or to low recharge.

Communication between various wells can be detected from the water/steam ratio plot for each well. For example, a slight increase in enthalpy of M-8 and M-31 can be observed when M-35 starts production in March 1974, indicating a good communication between these wells. The next well to come on line in this group is M-21A which appears to affect the enthalpy of M-8 without causing any apparent changes in the water/steam ratios of M-31 and M-35. This indicates good communication between M-8 and M-21A. However, the communication between M-21A and M-31 and between M-21A and M-35 is hard to interpret due to the large distances involved. A decrease in water/steam ratios in M-8 and M-31 is also observed when the new wells M-26 and M-29 start production. This shows good communication between M-29 and M-31. The slight increase in enthalpy of M-31 is

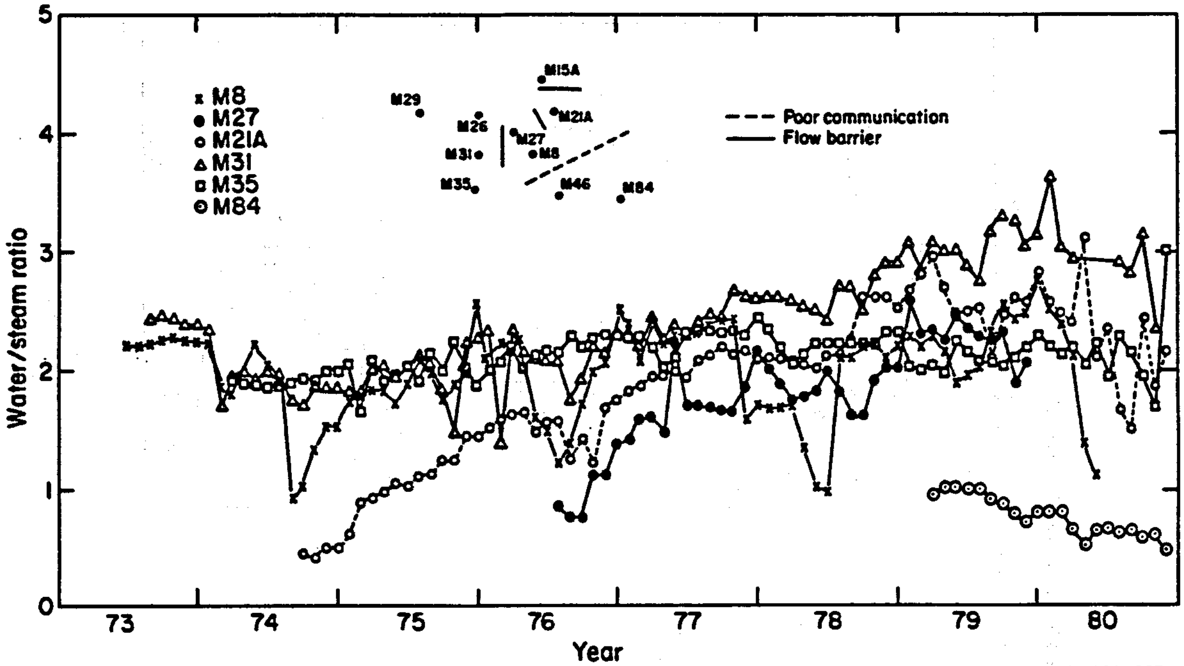

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Figure 7. Water/steam ratio versus time for wells in Group I.

probably due to a drop in WHP in August 1975 as shown in Figure 6. The coincident increase in enthalpy of M-8 is too small to conclude any communication with M-26. Another enthalpy increase of M-8 in early 1976 does not appear to have been caused by the opening of well M-29 located at a considerable distance.

Wells M-21A and M-35 do not appear to respond to well M-26, probably because they are too far apart. The effect of M-27 is clearly seen in well M-8 but not so clearly in wells M-21A, M-31 and M-35, probably due to poor communication. Another decrease in water/steam ratio in M-8 is observed when well M-46 starts production in September 1977. As discussed in connection with Figure 4, this increase in enthalpy is mainly due to mixing of fluids from M-8 and M-46 in the same separator. Other wells in this figure do not respond to M-46, probably because they are situated too far away from it.

The introduction of well M-15A does increase the enthalpy of M-8 without any observable changes in M-21A, M-27, M-31 and M-35. It is surprising to note that M-15A has no communication with nearby well M-21A but does communicate with well M-8 situated further away in the same direction. Going back to Figure 4, we find that a decrease in flow rate and rise in enthalpy in M-8 are not really caused by the opening of M-15A. In fact, what we see is a continuously declining flow rate in this well. The increase in enthalpy indicates a lower recharge to this well at this time. This trend is confirmed again in 1980 as shown in Figure 4. As a matter of fact, if the seismic event of mid-1978 had not occurred, this well might have been shutin in 1978 instead of 1980. No appreciable changes in water/steam ratios in wells of Group I were observed due to the initial production of M-84, indicating a poor communication between these wells and M-84. Figure 7 shows flow barriers by solid lines while dashed lines indicate poor communication.

Group II

Figure 8 shows the water/steam ratio versus time for wells M-5, M-14, M-15A, M-19A, M-20 and M-25 belonging to Group II. Well M-5 is the oldest producer in this group, followed by M-20, M-25, M-15A, M-19A and M-14. As may be noted, wells M-15A and M-20 are intermittent producers. Except for wells M-19A and M-20, these wells show significant changes in WHP. For example, the WHP of M-5 decreases from 20 kg/cm^2 in December 1973 to 6.3 kg/cm^2 in January 1974, probably due to change in orifice diameter. Thereafter, its WHP remaines almost constant.

The WHP of M-14 increases from about 7.6 kg/cm^2 in January 1977 to about 22 kg/cm^2 in March 1977 due to a change in the diameter of the production casing from 8 to 4.5 in. This change was made because of excessive sand production (CFE annex number 6). Well M-15A starts with a high WHP which declines over the years. The WHP of M-25 increases between November and December 1977 due to a reduction in the production casing diameter from 8 to 4 in. Excessive sand production is also the reason for this diameter change.

Continued production has caused a decline in enthalpy for most wells except M-20 which has shown an opposite trend. Toward 1978-80, well M-15A produces the lowest enthalpy fluids in this group while M-20 produces the highest.

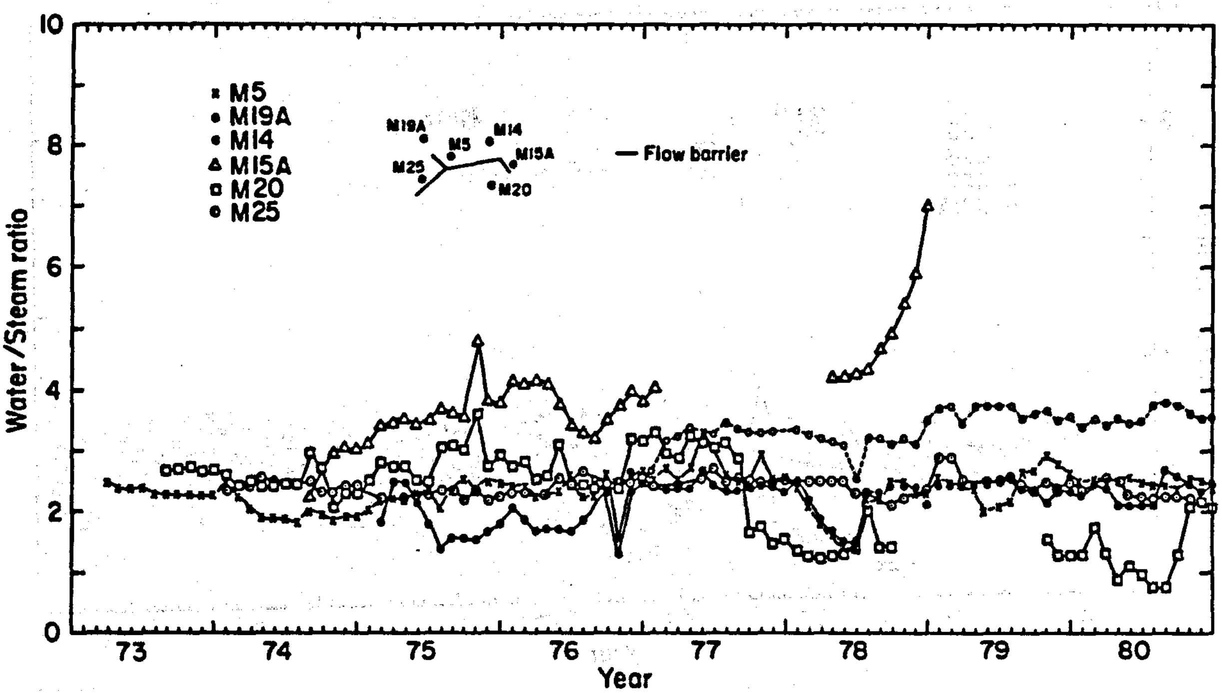

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Figure 8. Water/steam ratio versus time for wells in Group II.

Looking at Figure 8 there appears to be no communication between wells M-5, M-20 and M-25. Opening of well M-15A does not affect the water/steam ratios of M-5, M-20 and M-25 to any significant extent, suggesting poor intercommunication. However, during its reopening in April 1978, the enthalpies of M-5, M-19A and M-14 do show some increase, indicating good communication with these wells and communication barriers with wells M-20 and M-25. The opening of well M-19A shows some communication with M-25 and barriers with wells M-5, M-15A, and M-20. Comparing this effect with that during reopening of M-15A shows that communication probably exists between M-19A and M-5 and also between M-19A and M-15A. The reopening of M-20 in October 1979 indicates communication barriers between M-20 and wells M-5, M-14, M-19A and M-25. These inferred barriers between wells are shown in Figure 8.

Group III

Figure 9 shows of the water/steam ratio versus time for wells M-20, M-21A, M-25, M-26 and M-27 in Group III. It may be noted that the ratio increases with time for most of the wells in this group, indicating mixing with colder waters drawn into the system. During 1979-80, well M-20 is the hottest well and M-26, the coldest. Except for M-20, M-26 and M-27, the rest of the wells in the group have been in continuous production since 1974, when they were first put on line. As discussed before, if we analyze the changes in water/steam ratio with time, we determine the flow barriers shown in Figure 9.

Group IV

Figure 10 shows the variations in water/steam ratios with time in wells M-35, M-45, M-48, M-51, M-84, M-103 and M-181 in Group IV. In this group, the first three wells are completed in the α aquifer, and last three in the β aquifer. Well M-51 is completed both in the α and β aquifers. It has not been established so far whether there exists communication between the two aquifers (discussions during San Felipe Workshop, February 1982). Thus, it is necessary to interpret the interference between the wells completed in the same aquifer.

In Figure 10, it may be noted that the water/ steam ratios are quite variable for most wells in this group. M-181 is the coldest well in the group with a declining trend in enthalpy. M-84 and M-45 are the hottest wells showing increasing fluid enthalpies. Using the procedure discussed above, we find that there exists no communication between M-35 and M-45. Well M-48 is located some distance away and is unlikely to show any interference far from these wells.

Additionally, wells completed in the β aquifer (M-84, M-103, and M-181) do not show any interference between them, probably because of the larger distances involved. In fact, wells M-84 and M-103 start production at the same time (March 1979), a case to which this analysis cannot apply. Well M-181, being a cold well is also not suited for this analysis.

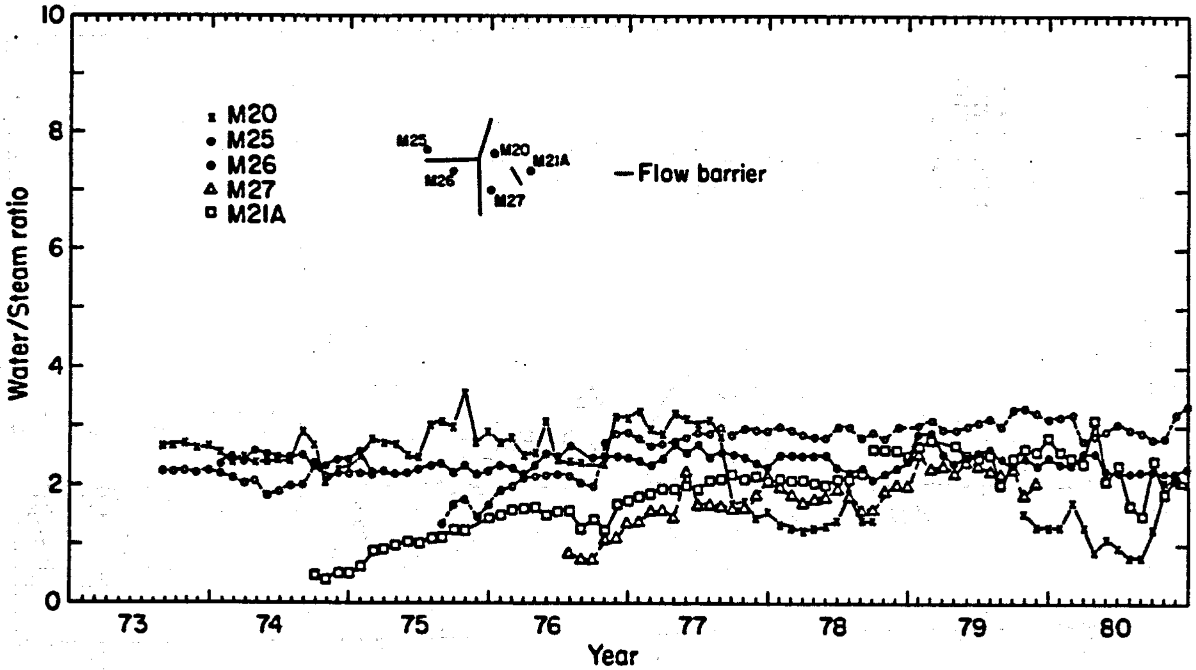

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Figure 9. Water/steam ratio versus time for wells in Group III.

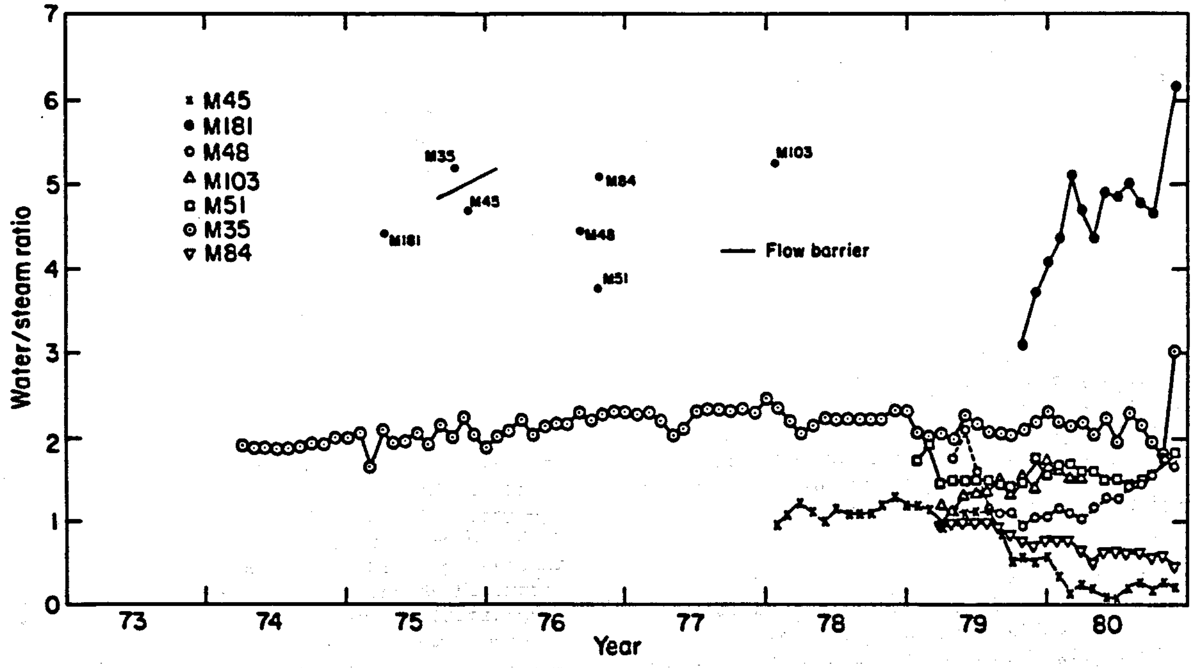

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Figure 10. Water/steam ratio versus time for wells in Group IV.

The flow boundary inferred from the data is shown in Figure 10. The flow barriers interpreted from Figures 7 to 10 are superimposed in Figure 3 over the heat and mass flux distributions in the field. Surrounded by barriers, it is now clear why the recharge to M-20 and M-45 is declining.

SUMMARY AND CONCLUSIONS

An areal distribution of heat and mass production in the Cerro Prieto field has been presented for two different times to determine the initial state of the α and β aquifers and the behavior of the field under production. It was found that, initially, the α and β aquifers were hot and very hot respectively. Cold boundaries to the field were found to be located toward the west and northeast.

Initially, fluid production from most wells was very high. M-53 and some wells southeast of Fault H produced very hot fluids at very high rates. Production from most wells declined over the years, possibly due to scaling in the wellbore, reduced recharge to the aquifer, high resistance to flow due to silica precipitation in the reservoir pores and/or relative permeability effects in the two-phase regions surrounding the wells. In most wells fluid enthalpies declined over the years, perhaps due to mixing with colder waters either drawn in from upper strata and/or from the cold lateral boundaries depending upon well location.

Interestingly enough, the fluid enthalpy of five wells M-20, M-45, M-51, M-84 and M-105, was found to be increasing with time. The recharge to these wells is expected to decline with time because of the presence of flow barriers whose existence was confirmed by enthalpy interference interpretations. Cold boundaries in the west and northeast appear to move toward the main field, reaching wells M-42, M-14, M-15A and M-21A in the northeast and wells M-30, M-31 and M-26 in the west in response to large-scale fluid production.

It is found that if a two-phase region surrounding a well is intercepted by other neighboring wells, its pressure and saturation temperature decline, resulting in increased fluid enthalpy due to heat transfer from the rocks and a decline in production rate due to reduced reservoir pressure. Such interference phenomena are found to occur in many wells in the Cerro Prieto Prieto field and are used to interpret qualitatively the degree of communication between Cerro Prieto producing wells.

Based on this study, flow barriers have been established between production wells. These barriers need to be confirmed by other studies; however, they appear to explain the low recharge to wells M-20, M-45 and also possibly to M-8.

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