**CUPET**

**Exploration – Production Direction**

**EPEP Majagua**

**Generalization of the Hydrodynamic Model**

**Pina Site**

### Majagua, November 2003.

# INTRODUCTION

The deposits of volcanic origin, rare in the world of oil exploration and exploitation, are extremely complex from the hydrodynamic point of view due to the great heterogeneity that they present.

One of the few regions of the world where this type of reservoirs are found is the so-called Central Basin that mainly occupies the provinces of Ciego de Avila and Santi – Spiritus, where a series of oil accumulations have been discovered, the main ones being those of Jatibonico (1954), Cristales (1956) and Pina (1990).

The Pina deposit has been exploited since 1990 at the depletion regime, in 1995 it reached the maximum production - thanks to the hydraulic fracturing works developed by Sherritt -, subsequently declining the volumes of crude extracted. After more than ten years of exploitation of the Pina deposit, where one million tons of oil has been extracted and this is in the last phase of exploitation, it is necessary to make a generalization of the hydrodynamic behavior of this type of reservoir, with the aim of having a document that facilitates the possible future exploitation of deposits of this type to be found in this area or others similar.

This document only aims to verify the facts regarding the hydrodynamic behavior and exploitation of the deposit for a possible extrapolation to similar reservoirs, as well as to generalize all the information that numerous authors have made on the subject.

# GENERALIZED LITHOLOGICAL CHARACTERIZATION

For a better study of the behavior of the deposit in the different packages, a classification of the producing rocks was made in terms of their granulometry, being grouped as follows:

## Fine Tuff

In this denomination have been grouped those rocks whose granulometry is less than one millimeter. Its texture, taking into account the nature of the fragments that compose it, is extremely varied and it cannot be said that a particular type predominates. However , it can be seen that the crystalline – vitreous and vitreous tuffs are slightly more abundant.

Regarding the processes of alteration it can be affirmed that practically all the rocks of this group are pelitized to a greater or lesser degree, as a result of the abundance of vitreous components, which are very susceptible to alteration to minerals of the clay group.

In this group, intercalations with sediments are frequent. They are also fine-grained, being very frequent clay rocks (argillites, tobaceous argillites) and clayey – carbonate (calcareous argillites and marls). However, the most frequent sedimentary rocks that are interspersed here are limestones, which usually have tobaceous components, which gives it greenish-gray colorations of various shades.

Due to their composition, all these rocks are andesitic.

## Thick Tuffs

In this group have been included, tentatively, not only coarse-grained tuffs and volcanic gaps, but also medium-grained ones, that is, all those whose fragments are greater than one millimeter in diameter.

According to the nature of the fragments, these rocks have two predominant textures that are the lithic and the crystalline – lithic and in noticeably smaller quantity the crystalline – vitreous.

The pelitization present in the rocks has acted with special intensity on the matrix, being frequent the chlorytization and the presence of magnetite.

In this group the basaltic composition tends to be abundant, as coarse-grained rocks and volcanic gaps are more frequently basaltic than andesitic.

With thick tuffs, some sediments are usually interspersed less frequently than with fine tuffs. Fragments of limestone and sandstones with tobaceous matrix can be found, as well as tobaceous conglomerates that are described as very coarse-grained rocks with fragments of marked rounding.

According to the fragments, the effusives predominate, the most abundant are the basalts and andesites, strongly altered by processes of cloritization, pelitization and zolitization. The matrix seems to be little abundant of clayey – tobaceous nature.

## Effusive

Only a small group of wells manages to cut this horizon. From the point of view of their chemism, there seems to be the rule that andesites and often basalts are found first lying under them. In general, the rocks are strongly cataclastic and have sometimes undergone a strong chloritization and pelitization.



# INITIAL RESERVOIR LAYER PRESSURE

The dependencies of the initial layer pressures with respect to the depth by blocks were elaborated, including the measurements during the test and those made in formation tests. The result shows the existence of over initial pressure loads of 7-11 at, (depending on the block) and do not reveal changes in the pressure gradients within the volcanics.

This is explained by several factors:

1. Poor accuracy of the initial layer pressure measurements made with Soviet pressure gauges in the years 1990-1995, with an error of 2-3%
2. In the past, during the stage of filling the traps, there was a greater degree of hydrodynamic communication between the layers than the current one. In addition, this process occurred over a span of hundreds of billions of years.
3. Although it is true that vertical communication between the layers is poor or practically does not exist in a group of wells, in others it can be inferred from the tests carried out in the different layers, that there are areas where this is much more evident, a fact corroborated by the drilling of infill wells, both vertical and horizontal in the reservoir with pressures 1/4 below the initial pressure of the reservoir.

Table 1: Initial layer pressures of the main blocks of the Pina deposit.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Block I (Thick Tuffs)  (Fixed to 990 mbbp) | | Block IV (Thick Tuffs)  (Fixed to 990 mbbp) | | Block III (Fine Tobas)  (Fixed to 990 mbbp) | |
| P-47 | 106.7 | P-122 | 100.8 | P-107 | 101.8 |
| P-50 | 110.88 | P-154 | 49.3 \*\* | P-104 | 102.6 |
| P-116 | 100.2 | P-32 | 103.9 | P-102 | 76.4 \*\* |
| P-120 | 106.5 | P-118 | 104.4 | P-22 | 109.0 |
| P-121 | 105.4 | P-119 | 93.2 | P-111 | 95.1 |
| P-123 | 112.0 | P-117 | 105.6 | P-110 | 94.7 |
| P-124 | 111.9 | P-200 | 75.1\* | P-100 | 73.6 |
| P-127 | 98.5 |  |  | P-103 | 100.2 |
| P-135 | 87.7\* |  |  |  |  |
| P-138 | 102.7 |  |  |  |  |

\* Wells drilled in 1996 and 1999 where interference from neighboring wells is noticeable.

\*\* Area of terrible collecting properties.

# HYDRODYNAMIC MODEL

The complexity of the site is defined, by the heterogeneous pyroclastic rocks and the successive intercalations of tobaceous horizons of medium and coarse granulometry, with detrital sediments, carbonate and clay intercalations, plus the clay itself that present a part of the tuffs themselves - mainly the fine ones - which print to the site particularities, given by its lithological-facial properties, that impose non-tectonic limits on complicated reservoirs.

From the lithological point of view the volcanics of Pina have separated into three fundamental Effusive layers, Thick Tuff and Fine Tuff. Its characterization is given in the 1996 calculation and was briefly exposed in chapter II of this work. The existence of sublayers of various petrophysical properties within these rocks is given in summary by:

* The peculiarities of the formation processes of volcanic rocks that give rise to variations in composition, granulometry, facie distribution in area and depth.
* The varying degrees of alteration of minerals to clay products.
* The degree of fracturing: according to Dr. R. Aguilera the density of fractures is inversely proportional to the power of the layers, it is also a function of the hardness of the rock; the plastic ones do not fracture or their fracturing occurs to a lesser degree than in the competent ones. Therefore vertical and subvertical fractures cannot have great extension. The fractured character of volcanic reservoirs is proven by previous core research, fieldwork and hydrodynamic research. In general, the unfractified areas of volcanic rocks show extremely low permeabilities of the order of 1 to tenths of milidarcy. Capillary pressure curves measured in samples from Pina reservoirs indicate pores saturated with water, so mobile oil is contained in fracture systems, and hydrodynamic communication through the porous matrix is unlikely. The flow of fluids will be by the fracture systems that are partially interconnected by means of microfractures that give rise to great hydrodynamic resistances to the movement of fluids. This great resistance is demonstrated by the great loss of energy that occurs in the reservoir where for each atmosphere of pressure drop only between 105 – 167 tons of oil are recovered depending on the lithological composition and the degree of fracturing of the rocks. The exception is hydraulically fractured wells where large fractures are created and the values set out above are multiplied by a factor ranging from 5 to 10.
* The communication between different areas of the reservoirs must be considered depending on the time factor. During the processes of migration and filling of traps that extend over millions of years there can be communication between the various parts of the reservoir. In the exploitation process the deadlines are months, and the key to both vertical and horizontal communication is the degree of fracturing analyzed in the previous paragraph, so two phenomena can occur: 1) Existence of packages with more or less clean rocks that present a high degree of fracturing that facilitates hydrodynamic communication. 2) Existence of areas with a more marked heterogeneity where due to the great resistances Hydrodynamics created by the microfract systems that interconnect the macrofractures develop compartmentalized areas not drained by the existing wells and that maintain reservoir pressures almost like the original. We must also consider the phenomenon mentioned in the literature that macrofractures tend to close - due to the effect of stress of overlying rocks - when the pressure of the fluids contained in them falls during the exploitation process, thus decreasing permeability and increasing incommunication.
* As a result of the low permeability that is generally observed in the reservoir, the drainage area of the wells can be considered relatively small. The drilling of the last infill wells drilled 200 meters equidistant from old wells or 150 m below the fine tuffs looking for the horizon thick tuffs in the horizontal wells drilled show that the areas sought were partially drained in all cases. (Fact corroborated by pressure data and production data from wells P-134, P-200, P-202, P-203, P-400 and P-401). This shows that in reality the drainage radii of the wells are greater than 100 meters. The great hydrodynamic resistance of the reservoir, which we talked about in the previous paragraph, means that the transfer of pressure from the drained areas to the undrained ones is very slow and 7 – 10 years later they have not reached 100 meters of drainage radius. This certainly occurs in areas with less fracture.

The above supports from the theoretical point of view both the existence of areas where vertical communication exists, as well as the existence of hydrodynamic isolation between layers and intercalations in volcanic reservoirs. (both assertions will be proven by facts that will be presented later)

The data provided by the exploitation of the Pina deposit indicate that the essential factor that governs the hydrodynamic behavior of the reservoir is the natural fracturing of the same and the knowledge of this factor is key when predicting the behavior of deposits of this type.

It must be considered that in some areas, there is communication between layers and between wells, but it is not a phenomenon developed throughout the reservoir, as well as others where this communication is much less evident and as explained above, both conditioned by a greater or lesser degree of local natural fracturing or product of stimulation work by the hydraulic fracturing method.

Below we will present both the information that indicates compartmentalization and that indicates hydrodynamic communication in the reservoirs which we have separated into two main groups:

* Hydrodynamic criteria based on the result of tests, Technical Geologist Measures (MGT), and well investigations: layer pressure measurements, RGP measurements, behavior of oil and water production.
* Geochemical criteria based on the properties of water and oil fluids.

## Criteria indicating compartmentalization within the reservoir

**Test results and MGT**

Well P-120

In Jun/93 began the exploitation of zone 1105-1094 mbmr, Efusivos, with initial Qp of 22.7 ton/d, initial Pc from 106.5 atm to 1047 m; in Dec./93 it was extended from 1088-1076 m, at the top of Efusivos, the Qp increased from 3.6 t/d per compressor to 13.42 t/ per upwelling, in Pc was measured from 56.8 atm to 1047 m for both intervals for an accumulated of 7087.4 ton representing 117.9 tons of oil extracted per 1 atm of layer pressure drop. In Dec./95 the interval 1055-1099 m was punctured in Thick Tuff, isolating with packer from lower areas increasing the Qp from 4.52 t/d (anterior zone) to 10 t/d, the Pf increased from 26.34 atm to 41.37 atm

In April/96 Pc of 72.3 atm was measured (in conjunction E + TG), this pressure is greater than that obtained in Dec./93 for effusives, being open effusive in conjunction with TG it is impossible to obtain the true value of the Pc for TG that is greater than 72.3 atm (effusive admits and does not allow the Pc to increase). In Dec./97 Pc was measured resulting in 38.2 atm for the E+TG horizons; In Sep./98 806-797, 736-724 m (top of TF) were punctured increasing the Qp from 4.2 to 14.8 t/d, Pc of 98.1 atm was measured.

Well P-47,

When puncing in Dec/91the first interval in effusives of 1133-1098 m, initially arises 10.4 t/d of oil; en January/95 layer pressure of 60.5 atm is measured, with a production of 2.9 t/d at a regime of 12 hours per day. Subsequently it was punctured from 1058-1036, 1026-1019, 991-977, 972-956 mbmr in Thick Tuffs with initial Qp of 21.7 t/d of oil by upwelling. In Sep/96, layer pressure of 74.7 atm is measured, after producing 2295 tons of oil and 586.7 Mm3 of gas from the new zone. (all pressures corrected to 1047 mbbp)

Well P-50

Start the production of Efusivos, range 1007.2-943.2 mbbp, the initial layer pressure was 103.5 at, , initial Qp of 6.0 t/d. In March/94 the SHERRITT Repunzó 1000-980 m (effusive), fractured with 8.4 tons of sand; and expanded from 923-907, 885-875, 857-837 m and fractured the first two intervals with 9.1 and 6.5 tons of sand respectively, increasing production to 78.0 ton/d after fracturing. In Jun-94 Pc of all open intervals is measured being 100.2, atm after producing 5306 tons of oil, this represents 1724 tons per at. of layer pressure drop; in Jun-96 Pc is measured again being 75.97 atm, with 1892 ton extracted by each atmosphere of layer pressure drop

( Np/Pc ) for this period. The high values of Np/Pc for this well indicate that hydraulic fracturing established hydrodynamic communication between it and the farthest fracture systems, not previously communicated (before the workovers). If we compare the Np/Pc figures of this well 1858 ton/atm with those corresponding to wells of the Pina field not fractured of 100-300 ton/atm the previous hypothesis is confirmed.

Well P-123

At the beginning of its production in May/95 it presented a P layer of 116 atm at 1095 value that corresponds to the pressure that theoretically would have a virgin area, not influenced by the extraction of neighboring wells; however at that time the P-124 well had accumulated 27059 tons of oil, 3563 m3 of water and an unquantified amount of gas, and the P-47: 5261 tons and 303 m3 of oil and water. These two wells are located 200 m each from the P-123 so it is evident the existence of permeability barriers between these wells, all producers of Toba Gruesa

Well P-118

This produced Thick Tuff interval of 1114 - 1065 m. The behavior of the layer pressures shows the decline of the same reaching 52.6 atm in May/95. In Mar/96 it was punctured from 858-848, 843-829 m, upper part of Fine Tuff, presenting gas and oil flow with RGP of 5562 m3/t, the measured layer pressure was 122.5 atm (both pressures corrected to 1200 m.)

Well P-32

The well was exploited in the range (1087-1057)(1017-977) mbmr, in October/93 layer pressure of 58.7 atm is measured. On 15/10/93, the interval 966-949, 946-943 mbmr is punctured, resulting in arising, with a high gas-oil ratio (unquantified). The well is kept closed but with both areas connected until 11/ 94 in which an R-4 packer anchored to 966-973 mbmr is lowered, maintaining - later -, the well closed until 11 / 97. In this period, layer pressure of the upper area was measured with the eometer, with the packer open below. As this is a gas zone, the measurement is incorrect using the level recovery curve method, the value obtained from 91.7 at is lower than the true corresponding to the layer pressure.

The analysis shows that the area maintained pressures similar to the original ones and therefore, this is further proof of the hydrodynamic isolation that we have been analyzing.

Well P-101

Since April/92 it produced from the range 851.2-757.2 mbbp, in Dec/97 it punctured 730.2-724.2 mbbp, increasing production to 16 tons / d of oil. The RGP that had maintained a decreasing trend for the lower zone reaching values of 52 m3/t increased to 1,200 m3/ton. On the other hand the layer pressures measured in the lower range show the depletion of this area reaching a Pc of 25.2 atm. (to 852 mbnm ). After enlargement, the layer pressure measured after producing 2240 tons of oil and 2.09 million m3 of gas was 75.5 atm (at 852 mbnm).

These results demonstrate the existence of an accumulation of free gas in the upper zone of the Fine Tuff. If there is communication between both punctured areas, the RGP instead of decreasing would have increased over time due to gas conification and the layer pressure would be in accordance with the measurement in the lower zone.

Well P-108

This well produced from the bottom of Toba Fina range of 856.2 - 777.2 mbbp, measurements of layer pressures show a decreasing trend reaching in Dec-98 to 44.9 at. In Dec- 98 the range of 691- 669, 665 - 638 mbmr, top of TF, with initial Qp of 31.4 ton/d is punctured, In Feb/99 layer pressure of 84.2 at was measured, after producing 2200 tons of oil and 1.6 million m3 of gas from the new zone.

Well P-115

It produced from the bottom of Fine Toba until it was punctured from 778-770, 752-744, 736-727 mbbp upper part of TF, presenting an increase in oil production from 5.9 to 25.3 t / d, in our opinion this increase is caused by the existence of greater layer pressure in the upper area, not drained by lower zone. Unfortunately in this case there are no measurements of layer pressures after enlargement.

Well P-49

This is a similar case to the previous one, when the upper part of TF was expanded, 787.2-781.2, 777.2-771.2 mbbp increased the extraction of crude oil from 1 t/d to 15 t/d. There are no layer pressure measurements after the last enlargement. As in the case of the P-115 the upper zone has upper layer pressure to the lower part of the TF

## Criteria indicating communication within the reservoir

The poor permeability of the Pina site is due to the elements exposed at the beginning of this chapter and in our opinion can mask in certain areas the existence of both vertical and horizontal communication. Previously we talked about the time factor in the processes of reservoir formation and exploitation which influences the idea that we may have about the hydrodynamic behavior of the deposit.

There is a fact that we consider transcendental when determining the hydraulic conductivity in the reservoir that is the drilling of infill wells. We will consider for our analysis only the wells that were drilled after 1996, that is, six years after the discovery of the deposit and fundamentally completed the main network of wells, all drilled equidistantly at 200 meters. We will talk about this factor later.

Now we return to the Geologist Measurements – techniques carried out that indicate communication by the vertical or the horizontal in a considerable number of wells. There is a possibility that some of these wells do not produce due to other reasons such as damage, poor testing or worsening of the collecting properties in a certain area of the producing horizon but in general a high percentage of the wells mentioned below by the data we have must have presented some fluid entry and were dry.

**Test Results and MGT**

Well P-110

Producing fine tuffs from the horizon since 1993, higher intervals of that same horizon were punctured in 1996 resulting in no increase in the inflow of oil. There are no measurements of layer pressures but it is inferred from the production results that in three years the oil from those upper zones was produced by the lower punctures.

Well P-104

Producing fine tuffs from the horizon since January 1992, higher intervals of that same horizon were punctured in 1996 resulting in no increase in the inflow of oil. There are no measurements of the layer pressures but it is inferred from the production results that in four years the oil from those upper zones was produced by the lower punctures.

Well P-138

After producing thick tuffs from the horizon for 3 years, fine tuffs were punctured in 1997 without observing an increase in the production of any fluid.

Well P-132

After producing thick tuffs from the horizon for 4 years, fine tuffs were punctured in 1997 without observing an increase in the production of any fluid. Fine tuffs are producers in this block.

Well P-129

It produced thick tuffs from the horizon since 1994 and in September 1998 the fine tuffs were punctured without observing the slightest increase in production. In this block the production of the horizon fine tuffs is demonstrated so it is possible that the neighboring wells after eight years find drained the oil contained in this area.

Well P-24

The cap on fine tuffs was punctured in June of '98, with an increase in gas production. Other wells in the area were punctured at the same hypsometric level in previous periods without observing notable increases in the Oil Gas Ratio, so it is inferred that in this case the vertical migration of the gas occurred forming a small secondary gas cap with pressures much lower than the initial pressure of the reservoir. The measured PC amounted to only 46.2 atm at 990 mbbp.

Well P-200

This well was one of the last to drill in the Pina deposit (1999) and already its initial pressure was below the initial pressure of the deposit (Tobas gruesas 75.1 atm at 990 mbbp). At the end of that same year the fine tuffs were punctured which turned out to be dry. The oil from that area had already been produced by neighboring wells drilled and punctured on that horizon.

Well P-202

Similar to the previous case. It was one of the last to drill in the Pina deposit (1999) and its initial pressure was already below the initial pressure of the deposit (Thick Tobas 99.1 atm at 960 mbbp). At the end of that same year the fine tuffs were punctured which turned out to be dry. The oil in that area had already been produced by neighboring wells drilled and punctured on that horizon.

Well P- 400

One of the horizontal wells drilled at the Pina field in 2000. Both areal and vertical communication is demonstrated by the low pressures found in the well, as well as that the fine tuffs were already completely drained because they did not present any fluid inlet.

Well P- 401

One of the horizontal wells drilled at the Pina field in 2000. Both areal and vertical communication is demonstrated by the low pressures found in the well, as well as that the fine tuffs were already completely drained because they did not present any fluid inlet.

**Results of wells drilled since 1996.**

Well P-135

Drilled in 1996 to the horizon thick tuffs of block I. Although the productions obtained in this well are considerable (for the Pina standarts ) some interference from the neighboring wells was already observed. We remember that this is the block of greater accumulated production within the deposit. The measured initial layer pressure amounted to 87.7 atm at 990 mbbp.

Well P-128

Drilled in 1996 to the horizon thick tuffs of block I. The initial pressure measured in this well is close to the initial pressure of the block. The well began its production with a high rate characteristic of the wells of this block but the duration of that period was much shorter than that of the neighboring wells so we consider that there was a small area with little or no influence of the neighboring wells that after a short period of production reached a partially drained area.

Well P-134

Drilled in 1997 to the horizon thin tuffs of block III and is a case very similar to the previous one. The measured PC amounted to 100.6 atm to 960 equal to the Pc of the block, it began with high productions but after a short period the production fell to less than 1 ton / day which shows that very quickly the drained limits within this block were reached.

Well P-200

Drilled in 1999 in block IV as the main target for thick tuffs. It presented an initial layer pressure of 75.1 atm to 990 mbmr, which evidences communication with neighboring wells. The expected cumulative production from this well is much lower than that of the other wells in the block.

Well P-202

Drilled in 1999 in block V as the main target to thick tuffs. The measured PC amounted to 99.1 atm to 960 close to the Pc of the block, it began with high productions but after a short period the production fell to less than 1 ton / day which shows that very quickly the drained limits within this block were reached. The expected cumulative production from this well is much lower than that of the other wells in the block.

Well P-203

Drilled in 1999 in block VI to the horizon fine tuffs. It presented an initial layer pressure of 37.3 atm at 990 mbmr, which evidences communication with neighboring wells. The expected cumulative production from this well is much lower than that of the other wells in the block.

Well P-400

First horizontal well in the Pina deposit. It was aimed at exploiting the thick tuff horizon of block III where a group of wells had only reached the horizon fine tuffs not reaching the objective proposed by this well. Although the layer pressure was not entirely depressed (79 atm to 990 mbbp), it can be clearly argued that the upper zones and neighboring wells were already draining a portion of the reserves contained in this area. During the drilling, a sludge of 1.15 g/cm3 was used, which meant a repression of more than 40 atm to the layer causing invasion of the mud through the fractures and considerable damage to the formation.

Well P-401

Second horizontal well in the Pina deposit. It was aimed at exploiting the thick tuff horizon of block IV where a group of wells had only reached the horizon fine tuffs not reaching the objective proposed by this well. In this block it was also observed that the pressure was 1/4 below the initial of the block and although it was tried to keep the weight of the mud as low as possible, technological difficulties prevented it from achieving it. It can be clearly argued that the upper areas and neighboring wells were already draining a portion of the reserves contained in this area. The production of both this well and that of the 401 was lower than the forecast made.

The above data provide us with a very important conclusion regarding the exploitation of the Pina deposit. The drilling of the Infill wells from 1996 (Preserving the initial distance between wells foreseen in the development of the 200-meter deposit) only managed to accelerate the extraction process of the field. Despite the poor permeability of the reservoir and the complexity of this type of lithology, it is shown that horizontally the drainage radii in general are greater than 100 meters. It is evident that after a certain production period (5-6 years) there is interference between wells.

From the economic point of view, the drilling of these wells was justifiable, since in all of them the financial parameters had positive values.

## Distance between wells in volcanic deposits

In this small section we want to expose our considerations on the ideal distance between wells to be able to reach optimal values in the exploitation in this type of reservoir. The economic criterion is the fundamental argument to carry out any action of development of an oil field and it is necessary to seek a balance between money and rational exploitation to achieve the highest possible indices in both aspects.

The determination of the distance between wells is an element that depends on many variables among which is the permeability, porosity, properties of the fluids among others and of course the integral economic evaluation of the development project. The reservoirs of the Pina deposit are heterogeneous and anisotropic in their petrophysical properties and petrographic constitution. Anisotropy is strongly revealed in permeability, which strongly influences the rate of extraction from the reservoir. If you want high levels of extraction (from the economic point of view it is recommended) it is necessary:

* Drilling of a dense network of vertical wells that drain the reservoir reserves in the shortest possible time: Method adopted in Pina, expensive where infill drilling demonstrated the partial drainage of the reserves at distances greater than 100 meters of drainage radius.
* Effective stimulation of the producing layer that increases production levels: In Pina hydraulic fracturing proved to be the only efficient method of stimulation where there were production increases between 5 and 20 times. This method indisputably allows, if its application in the development of a field is foreseen from the beginning, to increase the distance between wells. The drawback of this method is that it is expensive in the conditions of Cuba.
* Use of other techniques that tend to decrease the number of wells needed for the development of a field, for example the drilling of horizontal wells. In the stage that they were used, it did not allow to really assess their capacity for use in fields of these characteristics, although in the world it is a technique widely used with satisfactory results in all types of lithology and in deposits with the most dissimilar characteristics.

Of course there are special techniques to determine the behavior of the reservoir such as interference tests, which were not used in this reservoir which could greatly help determine this important parameter.

As a conclusion we can affirm that a network of wells equidistant 200 meters should not be the one used in the future because there are other techniques that allow the development of a field with a smaller number of wells achieving a better efficiency in the sweeping of the reservoir such as hydraulic fracturing (tested in Pina with very positive results) or horizontal drilling used worldwide with great success.

It is also necessary to carry out a whole set of special investigations to clear the unknowns necessary to achieve an efficient exploitation of the field, many of which were not executed in Pina.

## Dependencies of layer pressures with respect to accumulated oil extraction.

In the context of this work, the graphs of the dependence of the layer pressures measured with respect to the accumulated extraction of oil were made, in some wells such as P-40, P-27, P-124 the accumulated oil + water was considered. In most cases the dependence is linear, in others the layer pressures decrease exponentially with the increase in the accumulated oil; this allowed us to determine the value of liquid extraction by falling from a layer pressure atmosphere, shown in Table No. 2.

The non-included wells that presented production it was not possible to calculate this parameter because they did not present reliable consecutive measurements of layer pressures. In wells that do not appear and that did not have entry, this parameter is considered as zero, example P-51, P-35 and others. The summary of the above calculations is shown below:

**Np/P values for TG**

Number of measurements36

**Average166.68 ton/at**

Standard deviation371.52

Minimum0

Maximum1858 (Well P-50)

**Np/P values for TF**

Number of measurements38

**Average105.03 ton/at**

Standard deviation144.4

Minimum0

Maximum646.5 (Well P-27)

These results indicate that the volumes of oil in situ, reserves hydrodynamically communicated with each well are in most cases small.

***Table No 2* Np/Pc ton/atm** Values

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Well** | **Effusive** | **TG** | **TF** | Well | **Effusive** | **TG** | **TF** |
| P-2 |  |  | 135.90 | P-108 |  |  | 270.27 |
| P-3 |  |  | 646.49 | P-109 |  |  | 55.22 |
| P-21 |  |  | 158.14 | P-110 |  |  | 161.29 |
| P-22 |  |  | 123.92 | P-113 |  |  | 78.13 |
| P-24 |  |  | 71.47 | P-115 |  |  | 201.86 |
| P-27 |  |  | 560.79 | P-116 |  | 34.36 |  |
| P-28 |  |  | 126.58 | P-117 |  | 237.03 |  |
| P-32 |  | 74.38 |  | P-118 |  | 18.55 |  |
| P-33 |  |  | 27.86 | P-119 |  | 86.96 |  |
| P-40 | 454.55 |  |  | P-120 |  | 185.19 |  |
| P-41 |  |  | 197.30 | P-121 |  | 1222.25 |  |
| P-47 | 93.46 | 64.52 |  | P-122 |  | 357.36 |  |
| P-49 |  |  | 172.41 | P-124 |  | 670.45 |  |
| P-50 |  | 1858.06 |  | P-125 |  | 204.08 |  |
| P-67 |  | 65.79 |  | P-127 |  | 237.31 |  |
| P-100 |  |  | 134.60 | P-129 |  | 38.91 |  |
| P-101 |  |  | 159.79 | P-131 |  | 156.25 |  |
| P-102 |  |  | 53.76 | P-132 |  | 52.08 |  |
| P-103 |  |  | 135.14 | P-138 |  | 196.08 |  |
| P-104 |  |  | 270.27 |
| P-105 |  |  | 61.35 |

## Study of aquifers.

The study of the aquifers object of this research is a fundamental factor to define the hydrodynamic particularities of the deposit.

To undertake the work, we have tried to analyze in as much detail as possible the relationship between the areas with water input from the different wells and the behavior of the same, for the different layers and areas, where the accumulations of water seemed to have a certain relationship.

To study the behavior of the aquifer reported in wells P-27 and P-107, a correlation was developed between them and wells P-142 to the West and P-102 to the East, although the latter two did not reach the supposed aquifer. From them we analyze the following:

* Between P-27 and 107, there seems to be a lithological similarity in the lower intervals, analyzed by the Gamma register, although by the resistivity its similarity becomes less evident and the PS is nothing similar.
* Well P-102 did not reach the depth of the CAP determined by wells P-27 and 107. It has almost total absence of water so the aquifer may be limited in that direction.
* To the north, the P-40 well with the result of the numerous PFTs with oil inflows made, limits the aquifer in that direction.
* To the west, the P-142 well is not defining, as it had very small oil production; the records allow us to assume that the horizons are not similar. There was no water ingress and the reported is the product of an admission test.
* Although it cannot be specified with the elements we have if the aquifer of wells P-27 and 107 is the same, it can be perfectly accepted since there is a limited layer - the graphs of water and oil production ratify the limitation of the reference aquifer, although its volumes are greater than in other wells -, with similar reservoir properties and saturated with water and oil, with a contact at -863m, although from the hydrogeochemical point of view the waters are not similar.

Analysis of P-2 wells; P-100 and P-103, evidence that:

* The water area of the P-103 well has no relation to the aquifers of the other two wells, since the hypsometric level of the P-103 is lower than in the others. In that same position, the P-100 had oil input.
* The water production of the P-103 can be interpreted as contributed by the matrix, since it has produced 157m3 of water 2 727T of oil, which represents 5.4% of flooding.
* The aquifer zones of wells P-103 and P-2, have different characteristics, analyzing the complex of records- Gamma, Neutron, Resistivity and PS.
* The P-100 well has a water-saturated zone between two oil zones - in thick tuffs -, producing 18% of water, while the P-2, has only produced 320m3 of water and 10 088T of oil, which represents 3% of flooding.

Based on the above criteria, we can defend the hypothesis of the hydrodynamic isolation of the aquifers of this area. The petrophysical analyses carried out and exposed in the work of Calculation of reserves of the Pina Deposit, show that the matrix is saturated with water (Alvarez C. et, al. 1996) and this must be the reason for the incorporation of water in the production process, as high depressions originate during pumping.

Between wells P-103 and P-100, well P-22 was drilled, reaching depths greater than expected for the aquifer; however, during the test of the area, it was without entry. The water produced later in this well must be attributed to the productions delivered by the matrix in the exploitation process. Similarly, the P-26 in the same area, but located further north, also does not report the presence of any aquifer, but minimal amounts after a long production process, due to the incorporation of insterstitial water.

The behavior of known aquifers in P-53 wells; P-115 and P-49 were also studied using a correlation between them:

* The P-49 well, in Efusivos, presented a water inlet of 1.2 m3/d in the range 1185.58-1139.58mbmr (1128-1081 mbnm). The behavior of this aquifer will be discussed later with the remaining wells of the reservoir producing water in effusives.
* In the well itself and in the interval 980-960 mbmr an aquifer was studied that had an inlet of 1.9 m3/d in thick tuffs. Among the aquifers described is an oil zone, whose behavior has been explained by the presence of a ramp fault that separates them.
* The upper range saturated with water was known by PFT # 3 (868-930 mbnm), which had mud input that has been interpreted as saturated with water, because this is indicated by the experience of many similar results in the reservoir and the region. In the test of that layer at greater depth had water entry as well.
* The hypsometric level of this aquifer - in thick tuffs -, is above the hypsometric level of the oil-saturated horizon of the P-53 well - in fine tuffs -, so the aquifer lower than this oil-saturated zone should not be the same as the one mentioned in the P-49.
* The aquifer of the P-53, yes, can be related to the aquifer of the P-115 located between the previous two, being in similar hypsometric levels, both belonging to the fine tuffs. All this suggests that it is a limited layer with the same finite aquifer, as evidenced by the production curves of them.
* The aforementioned wells have an increase in water production at first, while in later periods they decrease to very low levels, while oil production maintains a behavior of an exponential type curve.
* The behavior indicated shows that the aquifer is not fed by infiltrational waters or other lower aquifers.
* The high salinities are due to the interaction of the limited water reserves with the lacing rocks, over a long geological period.
* The heterogeneous lithological behavior in the saturated water intervals in the thick tuff of the P-49, and those corresponding to the P-53 and 115 in fine tuffs, supports the hypothesis of independent aquifers for the last two, with respect to the first.

Of greater importance is the lower aquifer of the P-49 - in effusive - which could be interpreted as related to the water reported in the P-40 wells; P-47; P-120; P-123 and P 124, in effusives as well.

On the other hand, both the P-40; P123; P 124; P-127; they have similar behaviors in oil and water production, where the latter grow in the first stage and later descend demonstrating that aquifers are finite and without food.

In the same way, the existence of lower hypsometric levels to the East- in the P-3 around -1200 m and in the P-28 below -1200m, are data that must be taken into consideration.

The P-3 well represents an important element to assess the behavior of the aquifers of the reservoir. The well was tested through PFT from depths below -1600m there being no manifestation of water, on the contrary many manifestations of non-industrial hydrocarbons until the interval of 1160-1200 mbnm, where there was a weak entry of water into the PFT- in the effusives.

All the above, is in frank contradiction with the existence of a single aquifer in effusives and in favor of the existence of multiple aquifers that are formed in hypsometric positions not very different from each other, which can be attributed to the migration process in which the displacement of water by oil occurs in a part of the fractures, in addition to the fossil water that is kept in the matrix, as has been shown in petrophysical analyses.

# CONCLUSIONS

**Hydrodynamics of the Pina deposit**

* The reservoirs of the Pina deposit are heterogeneous and anisotropic in their petrophysical properties and petrographic constitution. Anisotropy is strongly revealed in permeability. Fracture systems are developed mainly in the NO-SE direction, as revealed by studies in the outcrops, FMS records, as well as the productive properties of the wells that depends directly on the degree of fracturing of the reservoirs. In front of the folds and near the faults, the rocks are more fractured. The southern flank of the folds is less fractured and the productivity of the wells is lower.
* Vertical communication:

1. Measurements of layer pressures show hydrodynamic isolation in a group of wells, between effusives, thick tuffs and fine tuffs, and even within each of these. Another group manifests hydrodynamic communication between the layers.
2. In other wells it is not possible - with the current information - to determine the degree of communication due to the lack of systematic layer pressure measurements during the exploitation process before and immediately after the MGTs were carried out. In addition, in most cases the investigations are not carried out with packers, to isolate the lower intervals, which they must undoubtedly admit; thus obtaining a value of the false layer pressure - lower than the real one.
3. The interpretation of the well records shows the existence of clay intercalations or highly altered vulcanogenic rocks and therefore flow barriers that act as local seals. Information included in the reservation calculation report.
4. The analysis of the curves of the behavior of the flooding of the wells during the exploitation process , shows that most of the wells do not present water intrusion by the vertical. The volumes of water are negligible and can be attributed to the expulsion of water from the matrix, during the fall of layer pressure.
5. In other wells, a noticeable flow of water is observed, which reaches a maximum and then a tendency to decrease. These data indicate that the aquifers are of non-significant dimensions, confined, where water expands thanks to the elastic reserves of the rock-pore-water system.

Regarding vertical communication, it can be concluded that: Volcanic reservoirs are not massive, but have multiple layers with a greater or lesser degree of hydrodynamic communication with each other. In some areas this communication may be greater due to the effect of fracturing, although we cannot forget the communication that can occur through the wells themselves that currently have several open areas, and also, due to the poor cementation of the exploitation jackets in most of the wells, as evidenced by the acoustic cementometry.

* Horizontal communication:

1. In most wells, no interference has been observed between them with respect to initial production and/or layer pressures, with some exceptions in the initial years of exploitation of the deposit. Interference tests were not carried out at this stage either and the pressures measured did not have the necessary accuracy to reach objective conclusions regarding this aspect. It is clear that hydrodynamic communication is very low, due to facial changes or permeability barriers, but the data obtained by infill drilling from 1996 corroborates the fact that horizontally the communication although bad is evident in almost the entire deposit.
2. The properties of the fluids: Oil and gas, show differences between wells which supports the hypothesis previously issued of very poor hydrodynamic communication, both horizontally, but more evident vertically.
3. The low values of the Np/Pc parameter indicate small volumes of fluids drained by each well.

* Drilling the infill wells showed that although the reserves expected to be extracted through them had already been partially drained, by neighboring wells, this was a very slow process that could take many years due to existing permeability barriers. Today it is not possible to delimit them for which it is necessary to apply other methods, for example interference tests, an aspect to be taken into consideration for future discoveries in reservoirs of this type.
* The study of the general characteristics of the deposit and its hydrodynamic behavior are demonstrative elements of the partial exploitation of the reserves with the current method of exploitation.
* The characteristics described above of the reservoirs of the Pina reservoir are extremely unfavorable for the application of water injection as an improved recovery method.

# RECOMMENDATIONS

Below we present our recommendations that aim to improve the exploitation rates in future discoveries in this type of reservoir:

1. **Perforation:**

* Drill with low weight sludge and clay inhibitor to decrease the possible damage of these sensitive formations.
* Run records that allow to determine the direction of the fractures as a fundamental element in the productivity of the wells.
* Use other drilling methods (directional, horizontal) with the aim of reducing the number of wells.

1. **Stimulation:**

* The only method that has truly succeeded has been hydraulic fracturing. Use this route to increase the volumes of oil to be extracted, as well as increase the distance between wells.

1. **Control of the holding:**

* Increase and systematize the measurements of layer pressures before and after enlargements, using packers to isolate the zones.
* Perform interference tests between wells using electronic pressure gauges and thus specify the existence or not of hydrodynamic isolation between wells that have the same layer open.
* Systematize the sampling of oil and water for analysis, which will allow to determine and control the variations of the physico-chemical properties of the fluids during the exploitation process, the compartmentalization of the reservoir, as well as the presence of channeling in the exploitation jackets.