Determining the Average Fracture Spacing between Fractures and Planning the Best Paths for the Wells in a Field Located in the Middle Magdalena Basin – Colombia

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Abstract

A Naturally Fractured Reservoir (NFR) has two different porosities and permeability regions denominated Fracture and Matrix Systems; the knowledge of the fracture spacing, is very important to adequately exploit the NFR, using this information we can understand better the relative subsurface rock strain and establish the fluid flow behavior for this kind of reservoirs; this considerations are very important and must be taken into account when planning the development of the well.

Dr. Wayne Narr developed a method for predicting the average fracture spacing from an analytic relationship based on the observation of the intersections between well – fractures and the porosity of the fracture. This method was applied at an oil field located in a Mid Magdalena Basin.

The evaluation was made using the data gathered through micro-electrical image logs run on large sections of the reservoir. The average spacing was calculated for each depositional sequence and also for the entire Productive Formation. This allowed the identification of those areas in the field that exhibited higher Fracture Intensity and determination of the stratigraphic targets that must be reached when drilling new wells in places where it is expected to attain higher hydrocarbon recovery.

Rose diagrams and Dip StereoNets were developed based on the available data on the fracture's array in the reservoir, which enabled the determination of the preferential strike and dipping of the main fractures. Then, a calculation of the (FIF) Fracture Intersection Frequency was made for those groups of fractures believed to act as the main contributors to hydrocarbons flow in the reservoir.

The interception of the fractures in a reservoir during drilling determine to a large extent, the success or failure of the projects developed in this kind of heterogeneous reservoirs. Therefore, it is the determination of the FIF as a function of the deviation, which provides a quantitative basis to make the best decision in regard to the magnitude of the deviation, and the direction it must follow.

Finally, FIF predictive diagrams were generated for five (5) wells. These diagrams enabled the establishment of the optimum dip angle and strike so as to achieve the maximum interception of fractures. Discrepancies were observed between these data and the dip angles and strikes taken while drilling the wells, which permitted establishing a base reference for future well drilling in nearby areas.

INTRODUCTION

NATURALLY FRACTURE LIMESTONE RESERVOIRS AND THE MATRIX AND FRACTURES SYSTEMS

To be able to store hydrocarbons a rock must be porous and permeable; meaning that it must have an inter-granular space able to store fluids and that volume must also be interconnected to allow fluid flow. There are several types of rock meeting such characteristics; among them we find sandstones, carbonates and granites.

Limestone is a carbonated rock with a bio-chemical origin, possessing both a low primary porosity and permeability (a primary property is that which is developed in the moment of the deposition of the sediment), but are able to develop a secondary porosity and permeability due to geological processes subsequent to the deposition of the material, e.g., tectonic activities, dolomitization or dissolution, and that is where this kind of rocks become of interests for the petroleum industry as potential hydrocarbon accumulators.

Primary and secondary properties differ greatly from each other, that is why the studies conducted on naturally fractured limestone reservoirs must be approached focussing on two totally different systems interacting between them, the matrix system and the fractures system; where the fractures system becomes the most important one, from the production point of view since it supplies the preferential permeability patterns.

In General, when a well is drilled in this type of reservoir and the well is producing, two types of flow are present, one denominated production flow occurring from the reservoir towards the well through the fracture system, and another a recharge flow occurring from the matrix system towards the fracture system.

The success of the projects developed in this type of reservoirs depends for the most part on the interception of the fracture system during the drilling of the wells; therefore, to correctly characterize the fracture system becomes a priority task if the reservoir is to be exploited efficiently.

This paper applies the methodology developed by Dr. Wayne Narr to calculate the average spacing between fractures and determine the best trajectories for drilling wells in naturally fractured reservoirs.

NATURALLY FRACTURED RESERVOIRS AROUND THE WORLD

There have been important hydrocarbon discoveries worldwide in fractured carbonates in all types of lithology and everywhere along the stratigraphic column.

During the 90's, seventy-six huge hydrocarbon reservoirs were discovered (with more than 500 MMBOE of recoverable reserves), the majority of these were in sandstones and carbonates, it is interesting to note that even though only eleven of the seventy-six discoveries were actually in carbonate reservoirs, they constitute one third of the recoverable reserves found.

In Colombia there are several fields with production associated to the presence of fractures, among the most important ones, we find Cupiagua, Floreña and Volcanera, which belong to the Llanos Basin, the Cira-Infanta and Guaduas in the Mid Magdalena Basin, Guando in the Bogota Savannah Basin, Tibu, Rio de Oro and Petrolea in the Catatumbo Basin and Cicuco-Boquete in the Upper Magdalena Valley Basin. In Colombia as well as around the world this type of reservoir represents one of the greatest hopes for the discovery of hydrocarbon reserves.

THE GUADUAS FIELD AND THE CIMARRONA FORMATION

The Guaduas field is located in the Mid Magdalena Valley basin on the foothills of the Eastern Cordillera in the Cundinamarca Department (Colombia), specifically in the Guaduas, Chaguani, Viani, Villeta, Quebrada Negra, Utica, Yacopi and San Juan de Rio Seco Municipalities.

This field began production in the middle of the year 2000, twenty-one wells were drilled and eleven have been producers; the accumulated production to date is 7.5 MMBbls of crude oil with an API. Rating of 19° degrees. According to studies previously conducted it is believed that the predominant production mechanism is Gas in Solution and by a lower percentage Initial Gas Cap Expansion.

The reservoir rock in the Guaduas Field is the Cimarrona Formation; which comprises three lithological units that from top to bottom are: limestone or sequence 3, a mixture of siliciclastic- carbonates or sequence 2, and laminated siliciclastics or sequence 1. *See Figure 1*. The Cimarrona Formation was also subdivided from top to bottom into ten depositional sequences, C0 to C9. *Figure 2*.

THE METHOD DEVELOPED BY NARR (Average Fracture Spacing)

This method is based on two models, the geological model and the mathematical model. These models are based on several assumptions that must be satisfied to assure their correct implementation.

The Geological Model

This model requires the fractures to be arranged in parallel with a preferential orientation, forming groups almost parallel to the layer, see *Figure 3*; if more than one group of fractures is present, each group should be analyzed separately, and the same should be done for each lithology.

The Mathematical Model

The mathematical model assumes that the fractures in the reservoir have an average height (H_{av}), an average length (L_{av}), an average aperture (A_{av}) and an average spacing (S_{av}), see *Figures 4a and 4b*; and it is based in the concept of fracture porosity, understood as the ratio between the empty space in the fractures and the reference total volume. Taken into account the above and under certain considerations the Average Spacing between Fractures (S_{av}) can be estimated from the *Equation (1)*.

$$S_{av} = \frac{A_{av} W_c H_c}{\sum_{i=1}^{n} A_i H_p} \quad (1)$$

Where:

S_{av}: Average spacing between fractures
A_{av}: Average aperture of the fracture
W_c: Core width
H_c: Core height
A_i: Fracture aperture
H_p: Partial height of the fracture

All these parameters can be determined through the core analysis and / or micro-electrical image logs.

Calculating the trajectory in directional wells

When a well presents a deviated trajectory through a fractured stratigraphic interval; the probability of intercepting a fracture is given by the ratio between the width of the zone where the fracture may be intercepted, called the success zone and the total width, where understood as total width the total width of the success zone plus the width of the zone where no fracture would be intercepted, called the failure zone. *See Figure 5 and Equation 2*.

$$P_i = \frac{success\ zone\ width}{success\ zone\ width + failure\ zone\ width} = \frac{T_p + D}{T_p + S_e} \quad (2)$$

Where:

$0 \leq P_i \leq 1$;
D: Diameter of the well
S_e: Effective spacing of the fracture
T_p: Effective thickness of the fracture
B: Angle between the well and the fracture

θ: Angle between the well and the stratification

Keeping in mind some considerations, the Fracture Intersection Frequency *(FIF)* can be expressed from the previous equation as follows:

1. In two dimensions (2D)

$$FIF = \frac{1}{L_d} = \frac{\cos\theta + (D / H_{av})}{S_{av}} \quad (3)$$

2. In three dimensions (3D)

$$FIF = \sqrt{\cos^2 \beta\, sen^2\theta + sen^2\beta(\cos^2 \theta + 2sen^2\theta)} * \left[sen\beta /(S\sqrt{sen^2\beta + sen^2\theta}) \right] + \frac{D}{S(H_{av})} \quad (4)$$

In some cases a 2D analysis is sufficient, nevertheless, when there is a presence of multiple groups of fractures in the reservoir, when the layer has a certain dip and when the limitations in the direction of the deviation do not allow orientating a well in a perpendicular direction to the fracture planes, it is necessary to perform a 3D analysis as it happens in the Guaduas Field.

When considering the possibility of drilling directional wells to intersect the fractures of the reservoir, determining the Fracture Intersection Frequency becomes a very useful tool, especially in those cases where it is necessary to intercept the greatest number of fractures during the stratigraphic advance of the well in an interval of the reservoir. Therefore, the knowledge of the FIF in function of the deviation provides a quantitative basis to make the best decision regarding the deviation magnitude and the direction of a well.

The frequency of fracture intersection increases as the well deviation magnitude increases (0 to 90º); but the rate of increase of the FIF decreases with the increase in the deviation of the well; therefore, the greatest increase in the Fracture Intersection Frequency occurs in the initial stages of the deviation. Therefore, the FIF variation rate in deviations greater that 70º is quite small.

The development of the equations above can be consulted in the AAPG Vol. 80/10, published in October 1996.

DETERMINING THE AVERAGE SPACING BETWEEN FRACTURES (S_{av}) IN THE CIMARRONA FORMATION

During the drilling of the wells in the Guaduas Field, very long cores were recovered, but some intervals do not clearly represent the density of the fracture, especially in the rubble zones. Therefore, it was decided to perform the evaluation using the data gathered from the micro-electrical image logs, which were run over huge sections of the reservoir. The only additional consideration when using these well logs is that the diameter of the well replaces the diameter of the core (W_c). Currently the well image logs do not permit visualization of some fractures that are visible in the cores, therefore, the fracture spacing estimated from image logs is considered conservative, meaning that in reality the fractures may present less spacing.

Fracture Arrangement in the Cimarrona Formation

Using the information available regarding the arrangement of the fractures in the Cimarrona Formation, Rose Diagrams and Dip StereoNet were carried out for nine wells in the field; after analyzing these diagrams it was established that the effective fractures considered as the producing system in the field are oriented in various directions, but these variations are very small and may be discarded, that being the reason why it may be assumed that all the fractures in a given group are exactly parallel.

In most wells the fractures show a preferential orientation NE – SW, with high dips (80º average). *See Graphs 1, 2, 3 y 4.*

Keeping in mind the arrangement shown by the fractures in the Cimarrona Formation and the arrangement of the wells in regards to them, and the stratification, the average spacing between fractures was calculated for each of the depositional sequences from C0 to C9, as well as for the totality of the Cimarrona Formation.

To obtain better results, the fracture aperture data was used individually. Likewise, it was established that the partial height of the fracture (H_p), determined by the diameter of the well and the angle between the well and the fracture (β), corresponded to the length of the trace read in the image analyzer (FVTL). Finally, it was established that the height (H_c), in each of the sedimentary sequences, corresponds exclusively to the sum of the thickness showing fracturing.

Results and Conclusions (S_{av})

1. The results show that the most fractured intervals in the Cimarrona Formation present Fracture Average Spacing between 0.45 and 4.96 m. *See Table 1.*

2. In most wells, the depositional sequences with less spacing between fractures are: C1, C2, and C3. It is important to point out that these sequences lithologically agree with the limestone and the calcareous siliciclastics identified in the upper part of the Cimarrona Formation. When comparing the porosity, fracture density, and spacing in the same interval, coherence is observed, this fact corroborates the results of this analysis.

3. On the other hand, the sequences showing the greatest average fracture spacing calculated for each well are: C6, C7, C8, and C9, which correspond to the lower part of the Cimarrona Formation or the laminated siliciclastics.

4. The analysis above allows establishing the principal stratigraphic objectives for the drilling of future development wells in sequences C1, C2, and C3. Additionally, according to the production analysis it has been demonstrated that these intervals contribute to the major percentage of hydrocarbon production.

DETERMINING FRACTURE INTERSECTION FREQUENCY (FIF) IN THE CIMARRONA FORMATION

Fracture Intersection Frequency (FIF) was determined for the main fracture group of the reservoir, that means those the fractures orientated in the NE – SW direction and with high dipping; to conduct this analysis it was taken into consideration the fact that the stratification presents an average azimuth inclination of 10º to 270º.

The fracture intersection frequencies were calculated using the FIF equation for a 3D model and θ and β were substituted in terms of geographical reference. Only five wells from the field were analyzed, where all the required information was available.

Graphs 5, 6, 7, 8 and 9 show the predictive diagrams of the FIF in 3D. In these illustrations the concentric thin circles forming the geographical frame of the reference, indicate the Fracture Intersection Frequency at a scale of 0 to 4.5 fracture/meter, the colored curves show the deviation magnitude of the well (0 –90º) in relation to the vertical. The interception of the colored curves with the concentric circles determines the magnitude and direction of the deviation of a well.

The FIF graphs from the wells in the Guaduas Field do not conserve the symmetric shape characteristic of the horizontal layer, since even though, only one group of fractures was considered, these are arranged in inclined layers.

FIF Results and Conclusions

The following are the results obtained after implementing the method developed by Dr. Narr, to establish the fracture intersection frequency in five wells at the Guaduas Field:

1. The Guaduas–1 well crossed the Cimarrona Formation with an azimuth of 37.4º and an inclination of approximately 21.29º. According to *Graph 5* of the FIF, the well was able to intercept 3.6 fractures per every meter drilled, nevertheless it can be observed that a trajectory of 17º azimuth and an inclination of 50º 60º would have reached a greater fracture interception (4.2 fractures/meter), therefore, to drill new wells in nearby areas, it is recommended to take such trajectory where it is expected to intercept the greatest number of fractures and obtain a greater production of oil. For this particular case, the effect of the inclination of the stratification is not very representative, since the dipping is relatively small (18º).

2. The FIF graph and the trajectory described for the Guaduas-2 well, indicate that this well was drilled in the opposite direction (214º/26.8º) to the maximum fracture interception possible (30°/40°-50°) where a maximum FIF of 4.1 fractures/meter could have been reached, *see Graph 6*; It is recommended to take such trajectory when drilling wells nearby.

3. The Guaduas-9 well was drilled with a 60° course and a 16° deviation reaching a FIF of 3.6 fractures/m (*Graph 7*). Likewise, it is observed that the rate of change in the FIF after 30° is quite low, to cut across a greater number of fractures, it is recommended to drill with an azimuth of 15° and a deviation of 40° - 50° in nearby areas in order to intercept a maximum of 4.3 fractures/m..

4. Keeping in mind the trajectory used to drill the Guaduas-3 well (53.8°/25°), it was established that this well was not drilled at an optimum direction, since only a FIF of 2.6 fractures /m was reached and it was not taken into account the dipping of the layer (22°). *Graph 8*, of the FIF shows that with a 20° azimuth and a deviation between 60°-70° an interception frequency of 3.3 fractures/m can be reached, if the conditions allow it during the operation.

5. Finally, the drilling conditions for well Guaduas-7 were analyzed. That well cut across the Cimarrona Formation with an azimuth of 52° and an inclination of 15.25° (*see Graph 9*). When such trajectory is drawn over the FIF graph, it can be seen that under those conditions the well only reached a fracture intersection frequency of 2.3. To optimize the trajectory of future wells in that area it is recommended to drill with an azimuth of 12° and a 50° deviation with respect to the vertical, thus expecting to obtain a maximum FIF of 2.7 fractures/m.

6. In general the wells analyzed were not drilled using the optimum direction and inclination needed to reach the maximum fracture intersection frequency; in the case of the Guaduas-2 well the decision to drill in the SSW direction was taken because towards the greater FIF direction the drainage areas of neighboring wells would have been interfered with. Furthermore, to make the most accurate decision regarding the trajectory of a well, it is fundamental to keep in mind the technical and operating limitations that may arise during the stratigraphic advancement of the well.

Table 2 shows the increase in the fracture interception frequency that the wells would have reached, if the trajectory calculated using the Narr method had been followed.

ACKNOWLEDGEMENTS

The authors express their gratitude to SIPETROL S.A. and FLAMINGO OIL S.A. for its technical and logistical support as well as for the indispensable collaboration provided for this study. Gratitude is also expressed, particularly to a: Andres Fuenzalida Etcheverry, Simón Hincapie H., Juan Carlos Alzate, Juan

Marroquín and Armando Correal; for their advise, knowledge contribution, collaboration and conduction in the implementation of this work.

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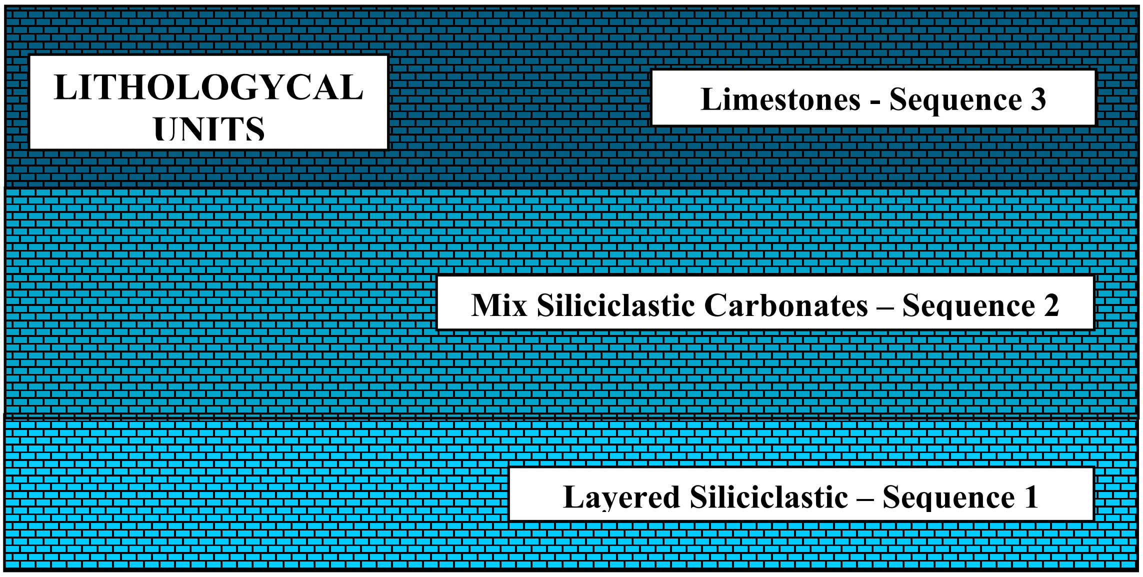


Figure 1. Lithologycal Units Cimarrona Formation.

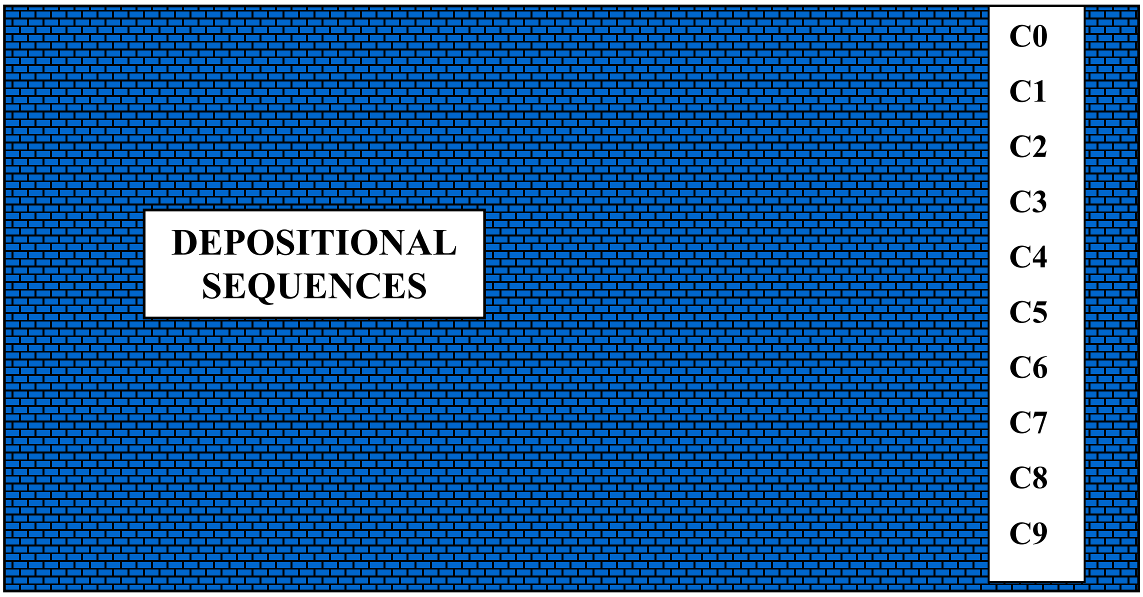
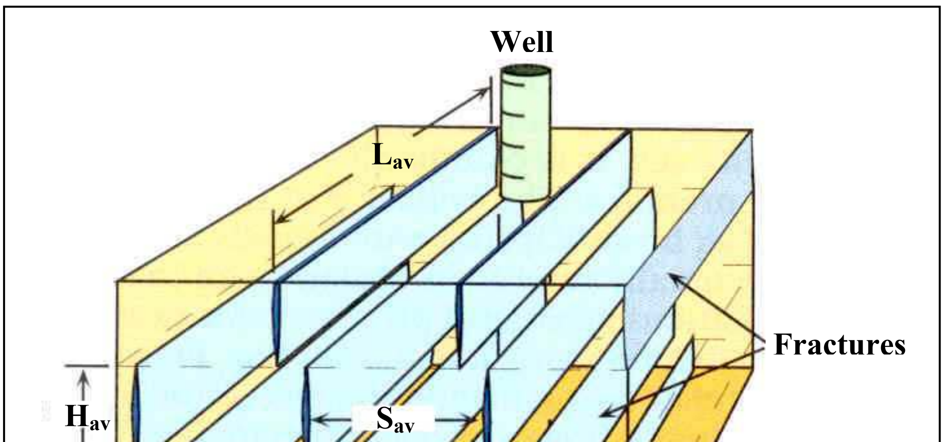
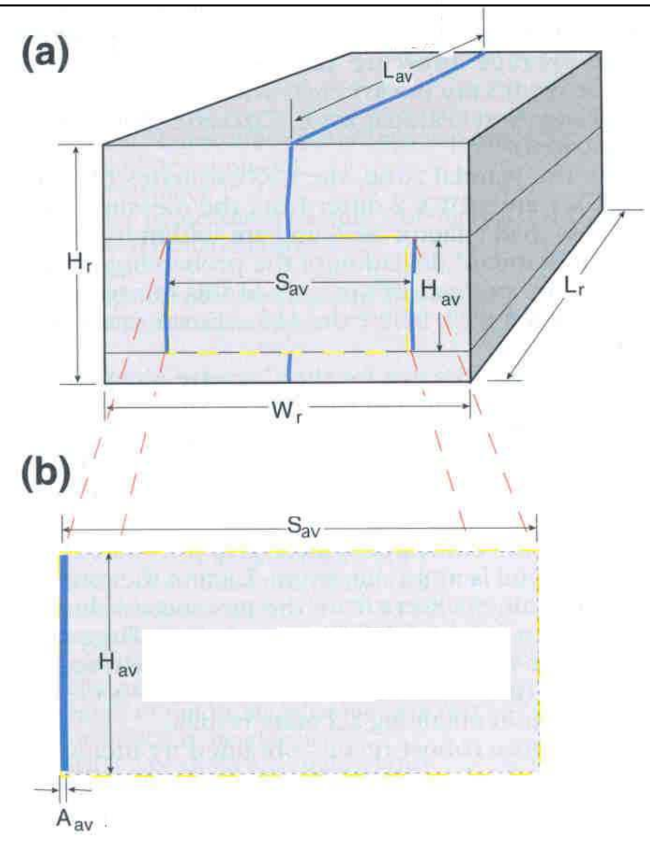


Figure 2. Depositional Sequences Cimarrona Formation.



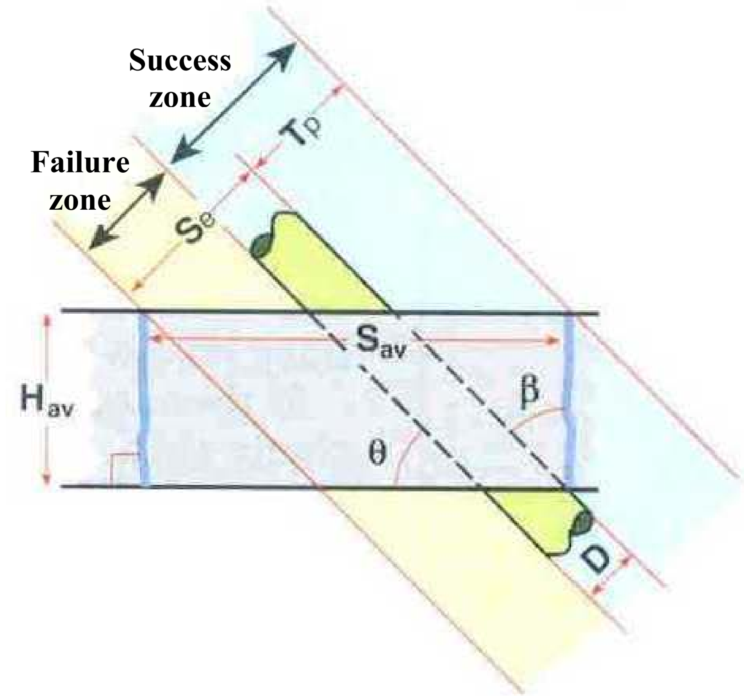
Source: Narr, W. AAPG Bulletin, Vol. 80 # 10 (October 1996)

Figure 3. Geological model of fracture arrangement in the reservoir.



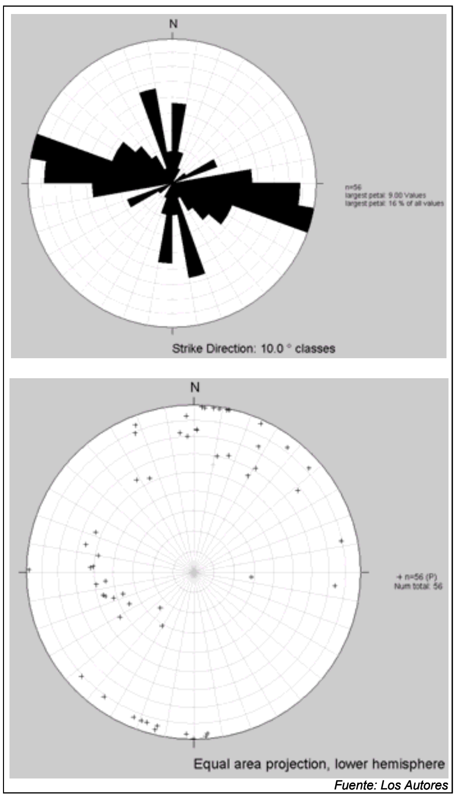
Source: Narr, W. AAPG Bulletin, Vol. 80 # 10 (Oct. 1996)

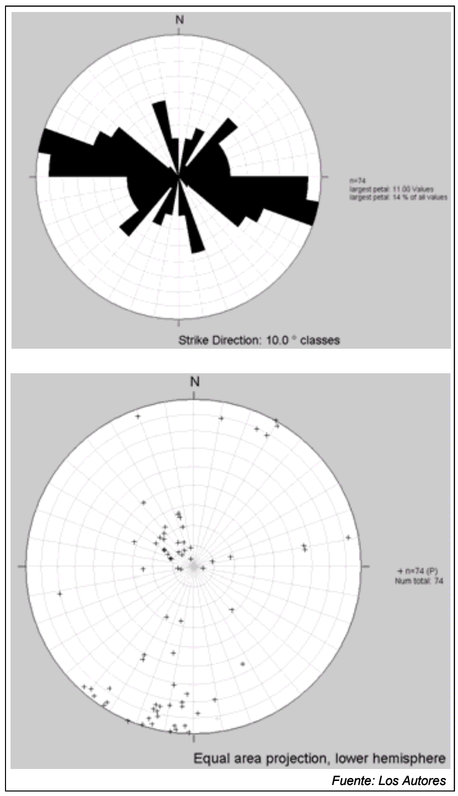
Figures 4 (a) y 4 (b). Idealized model of the fracture arrangement in the finite volume of the reservoir.



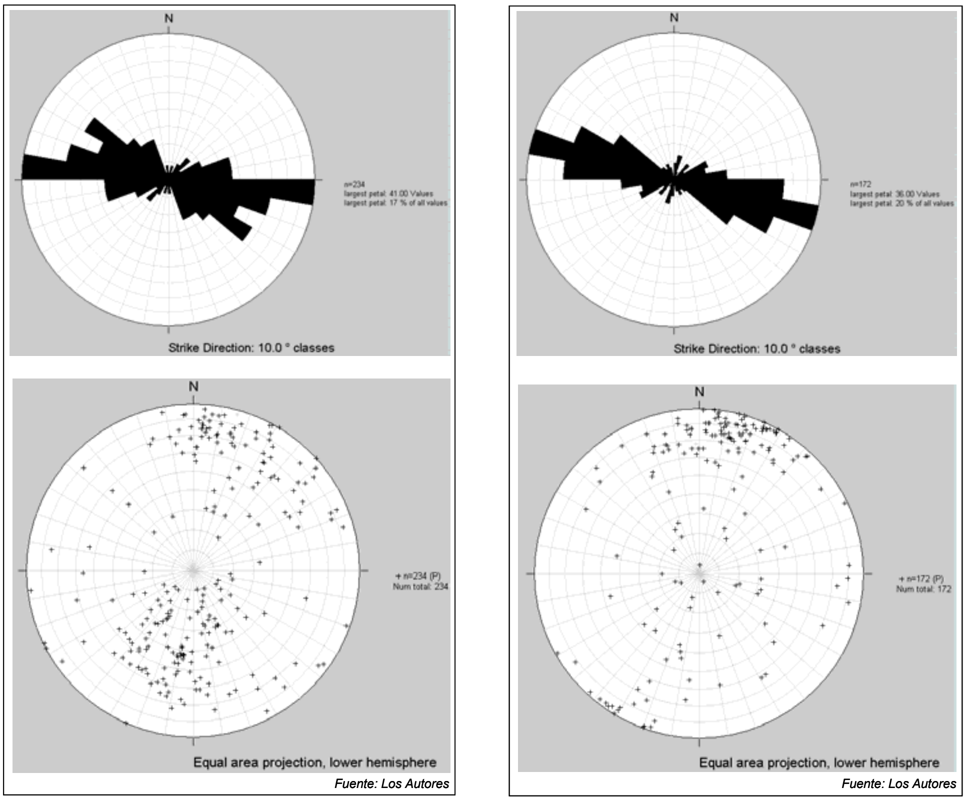
Source: Narr, W. AAPG Bulletin, Vol. 80 # 10 (October 1996)

Figure 5. Geometrical relation of the fracture intersection probability across a stratigrafic interval.

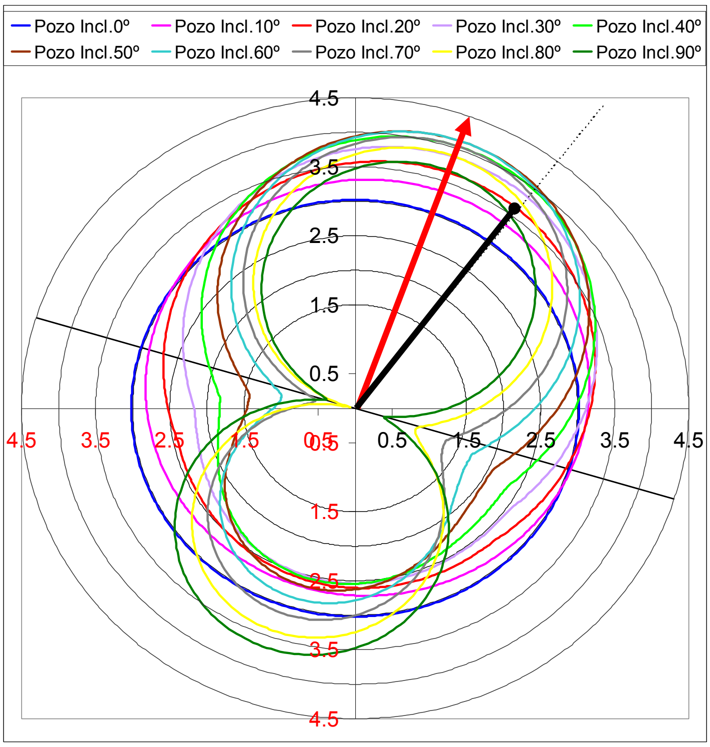




Graphs 1 and 2. Direction Rose and Dip StereoNet (Effective Fracture) Guaduas 1 and 2 Wells.



Graphs 3 and 4. Direction Rose and Dip StereoNet (Effective Fracture) Guaduas 9 and 7 Wells.



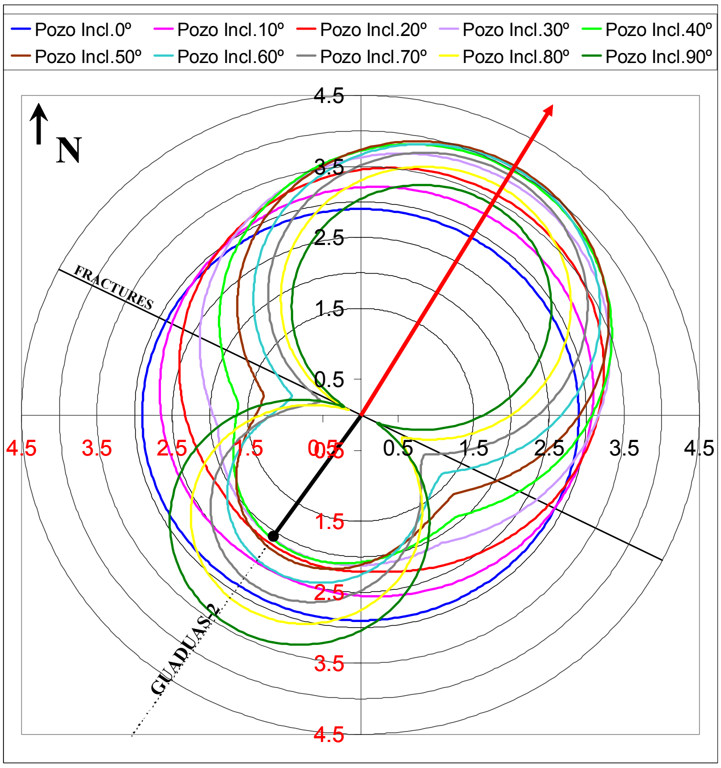
FIF Guaduas–1 Well

Well Trajectory: 37.4º/21.29º
Fractures Dip: 197º/80º
Fractures Direction: 107º
Stratification Dip: 223°/18°
$H_{av:}$ 0.0421m
$S_{av:}$ 1.7 m
Optimum Drilling Direction

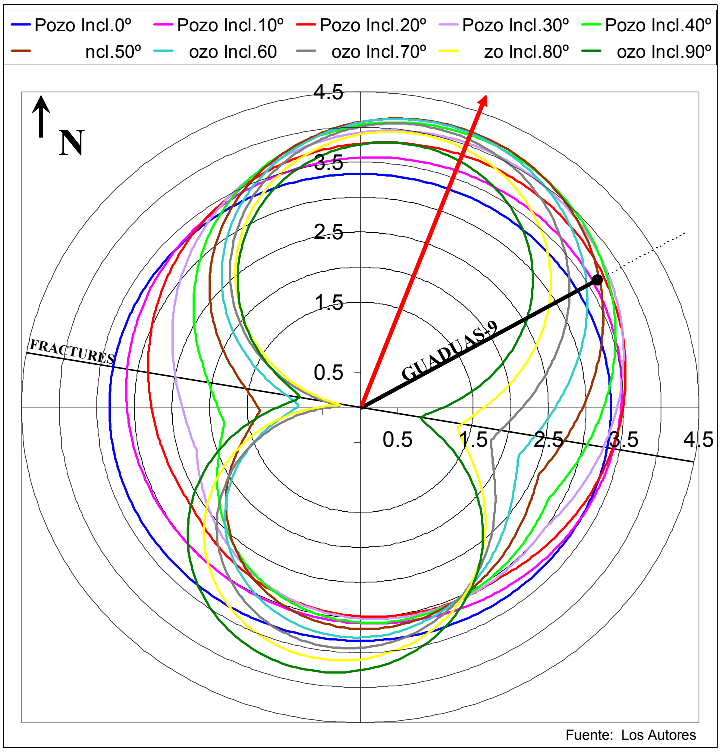
Graph 5. Predictive Diagrams of Fracture Intersection Frequency Guaduas-1 Well.

FIF Guaduas–2 Well

Well Trajectory: 214º/26.8º
Fractures Dip: 207º/73º
Fractures Direction: 117º
Stratification Dip: 225°/17°
$H_{av:}$ 0.0678m
$S_{av:}$ 1.27 m
Optimum Drilling Direction



Graph 6. Predictive Diagrams of Fracture Intersection Frequency Guaduas-2 Well.



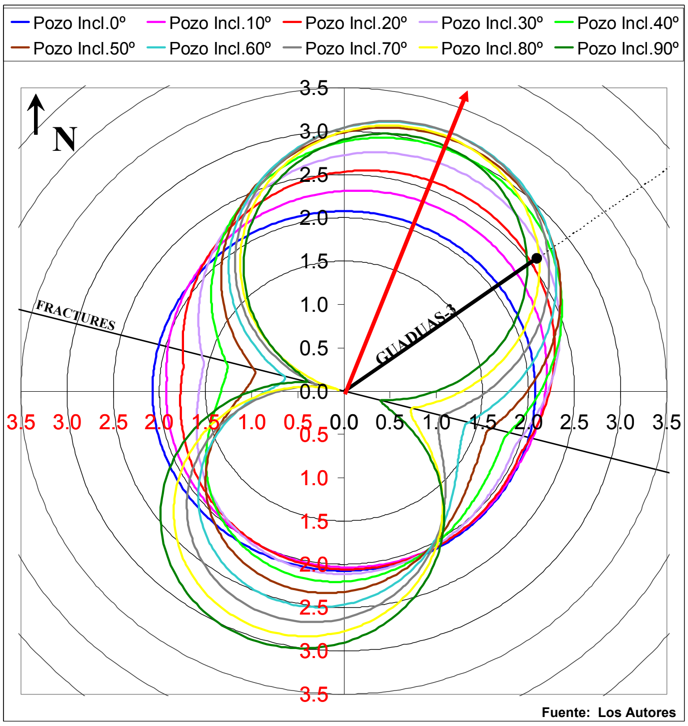
FIF Guaduas–9 Well

Well Trajectory: 60º/16º
Fractures Dip: 190º/76º
Fractures Direction: 100º
Stratification Dip: 275°/15°
$H_{av:}$ 0.0526m
$S_{av:}$ 1.31 m
Optimum Drilling Direction

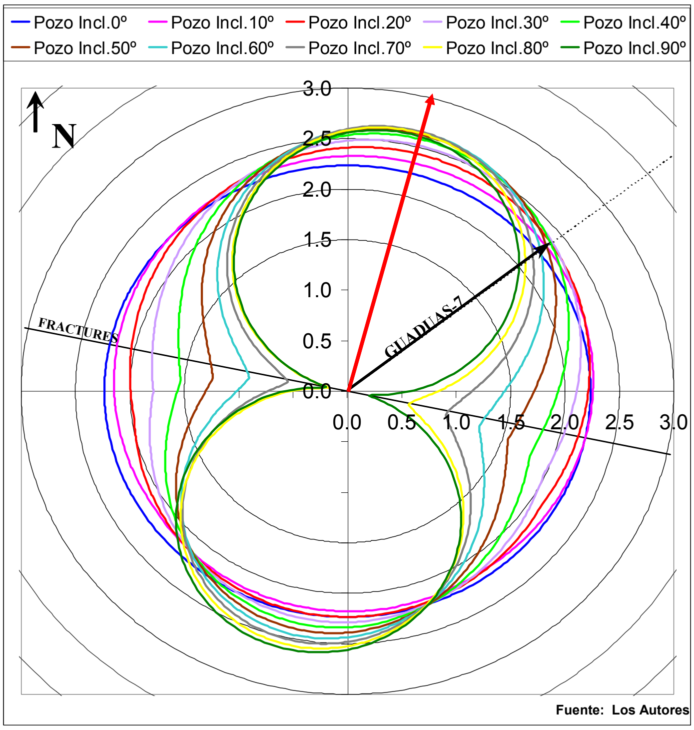
Graph 7. Predictive Diagrams of Fracture Intersection Frequency Guaduas-9 Well.

FIF Guaduas–3 Well

Well Trajectory: 53.8º/25º
Fractures Dip: 195º/88º
Fractures Direction: 105º
Stratification Dip: 225°/22°
$H_{av:}$ 0.0698m
$S_{av:}$ 1.4 m
Optimum Drilling Direction



Graph 8. Predictive Diagrams of Fracture Intersection Frequency Guaduas-3 Well.



FIF Guaduas–7 Well

Well Trajectory: 52º/15.25º
Fractures Dip: 192º/83º
Fractures Direction: 102º
Stratification Dip: 310°/6°
$H_{av:}$ 0.0451m
$S_{av:}$ 2.2 m
Optimum Drilling Direction

Graph 9. Predictive Diagrams of Fracture Intersection Frequency Guaduas-7 Well.

Depositional Sequences	Wells								
	G-1	G-2	G-3	G-4	G-5	G-6	G-7	G-8	G-9
C0-C1	-	4,96	-	-	-	-	-	0,65	-
C1-C2	2,33	0,66	1,14	-	-	-	0,80	0,45	-
C2-C3	1,33	0,54	0,48	0,53	-	0,96	0,58	0,73	0,91
C3-C4	0,68	0,59	0,50	2,11	0,60	1,67	0,80	1,65	1,52
C4-C5	1,31	1,14	0,88	1,80	-	-	3,02	3,49	3,24
C5-C6	0,86	0,65	1,26	1,67	3,05	3,06	2,19	1,48	3,23
C6-C7	1,09	1,04	2,28	2,58	-	4,37	2,04	-	1,46
C7-C8	2,13	2,19	2,28	1,58	1,94	-	3,80	-	1,29
C8-C9	2,09	4,88	-	-	0,92	-	3,13	-	-
C9-PF	1,43	1,75	-	-	-	3,55	3,64	-	-

Table 1. Average Fracture Spacing for the depositional sequences of the Guaduas Field Wells.

Well	Trajectory across the Cimarrona Fm.	FIF Well	Optimum Trajectory	FIF máx.	Increase Percentage
Guaduas-1	37.4°/21.29°	3,6	22°/50°-60°	4,2	16,7%
Guaduas-2	214°/26.8°	2,2	33º/40º-60º	4,1	86,4%
Guaduas-9	60.16°/16°	3,6	18º/40º-60º	4,3	19,4%
Guaduas-3	53.8°/25°	2,6	20º/60º-70º	3,3	26,9%
Guaduas-7	52°/15.25°	2,3	18º/50º-60º	2,7	17,4%

Table 2. Fracture Interception Frequency Comparison.

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Worked at SIPETROL S.A. from May 2001to June 2002 where he prepared his University Thesis on Reservoirs. Operations Engineer since September 2002 to this date at FLAMINGO OIL S.A. Functions includes Crude Transit and Delivery Co-ordinator at the Rubiales Field (Colombia). Operations and Cost Control Co-ordinator at the Rubiales Field. Currently, Co-ordinator for new businesses in Venezuela.

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