A Cretaceous Carbonate Reservoir in Transpressional Structures Producing from Fault-Associated Fracture Systems, La Concepción Field (Maracaibo Basin).

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Abstract

The La Concepción field (Maracaibo Basin) is mainly composed of two almond-shaped pop-up zones striking NE- SW forming uplifted blocks bounded by opposite reverse (oblique-slip) faults which curve towards each other. Integrated in an overall structural model based on faulted en echelon folds, we interpret such structures as dextral transpressional stepovers caused by strike-slip to wrench tectonic processes. Further tectonic events added normal fault network and pure strike-slip corridors.
The successive transpressional – extensional and strike-slip stress fields generated various sets of fractures with many different directions. Integration of 3D seismic, acoustic image and production log analysis reveals the clustering of productive fractures around fault zones. These open to semi-open fractures strike NW-SE and seem to be linked to the present day tectonic stress regime acting in this part of the Maracaibo basin.
Build-up tests exhibit three main types of response: (i) A-type displays a radial flow without testing boundaries in extended times, (ii) B-type showing a short radial flow period followed by bilinear flow and (iii) C-type is related only to bilinear flow. These three kind of flow responses are linked to the structural model of fault associated productive fractures.
Analysis of geologic and production data suggests that the spatial distribution of productive fracture zones is mainly controlled by tectonics and to a lesser degree by stratigraphy. A better understanding of the productive system allows us to optimize the drilling location and to select the adequate well completion.

Introduction

The La Concepción field is located on the western side of the Maracaibo Lake, Western Venezuela (Fig.1). It covers a surface of 248 km^2, bounded by the oil fields of La Paz and Mara to the northwest, Sibucara to the east, and Boscan to the south. The field produces from two reservoirs superposed in a normal succession: the Cretaceous fractured carbonates of the Cogollo Group (Maraca, Lisure and Apon formations) and the Eocene siliciclastic Misoa Formation. Both reservoirs are separated by non-producing formations (Upper Cretaceous shales and Paleocene sandy limestones) but tectonically linked (Marchal *et al*., 2003). The two distinct superposed reservoirs produce a light to medium oil. Eocene and Cretaceous reservoirs have subequal oil cumulative reserves, but the Eocene reservoir produces from a lot of wells whereas the Cretaceous reservoir produces from few wells.

Fig.1 - Location map of La Concepción (LC) Area.

The Cretaceous reservoir has produced 68 MMbbls of oil from 16 wells up until 1997. Since 1998, reactivations and drilling of sidetracks and new wells resulted in increase oil rates (2,000 to 17,000 bopd). The depth of the Cretaceous reservoir varies between 9,000 and 13,500 feet.

Nevertheless, even if the Cretaceous fractured limestones present large production rates in some wells, targeting the permeable system may be highly risky. Many fractures fall below the seismic resolution, and well information is too discrete to be the only tool to rely on. In spite of these difficulties, understanding of the fault-fracture-production relationship can significantly optimize new drilling locations when above-seismic-resolution fractures are sought.

Geological Settings

Regional Framework

La Concepción field is located in the northwestern part of a triangular structural block delimited by major basement-involved wrench fault systems, respectively the Oca fault to the north, the Bucaramanga fault to the SW, and the Bocono fault to the SE. The regional tectonostratigraphic setting for the Cretaceous in the Maracaibo Basin is one of a passive margin sitting on the Guyana Shield (Audemard, 1991). The geological history of the Maracaibo basin is closely related to the strike-slip movement of the Caribbean plate, inducing transpressional deformation during the Andean tectonic event (early Tertiary). Other contributors to the development of the basin are the formation of the Perija mountains (Oligo-Miocene) and Mérida Andean mountains (Plio-Pleistocene).

The interaction between these multiple tectonic events generated the foredeep basin in the western Venezuela (Audemard & Lugo 1996). These events, associated to the sea level variations and the great amount of sediment available, originated a very thick sedimentary section, which suffered various cycles of thermal maturation, forming numerous petroleum fields such as those in the La Concepción area.

Field Stratigraphy

In La Concepción Field, the basement consists of Permo-Triassic granites and schists (Fig.2). The base of the Cretaceous is composed by quartz-feldspar conglomerates and sandstones of the Rio Negro Formation. Overlying this formation are the Cogollo Group and La Luna Formation. The Cogollo Group is composed from bottom to top by the Apon, Lisure, and Maraca formations. The Apon Formation consists of limestone, locally dolomitized, intercalated with shales. The Lisure and Maraca formations are made of interbedded bioclastic limestones. La Luna Formation, considered the main source rock, represents the maximum flooding member of the area and consists of black shales and limestones. Capping La Luna Formation is a thin section of marine carbonates, named Socuy Member, composed by hard limestones and calcareous shales. The Colon - Mito Juan Formation, composed by thick black shales acting as the seal for the reservoir, overlies this member.

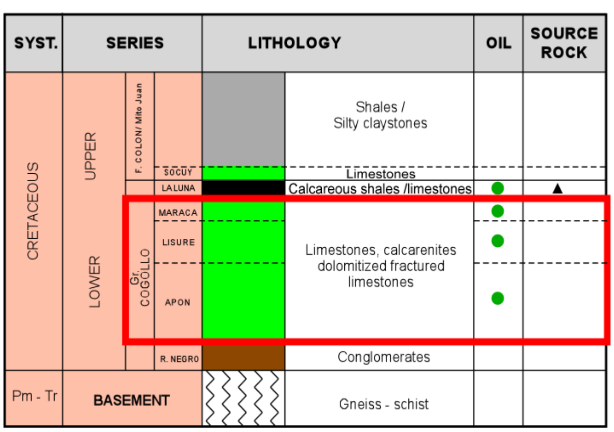


Fig.2: Stratigraphic Column of the Basement - Cretaceous sequence in La Concepción field.

Field Structure

The structural style of the La Concepción field corresponds principally to a deformation induced by wrench faulting involving high angle basement faults (Marchal et al., 2002) (Fig.3). The Cretaceous section is mainly affected by localized major reverse faults producing pop-ups. The overlying shales of the Mito-Juan Formation act as a ductile layer, responsible for the partitioning of the deformation between the Cretaceous and the Tertiary section. The Tertiary section is characterized by reverse-fault-limited fold to pop-up structure where normal faulting is common (Marchal et al., 2003).

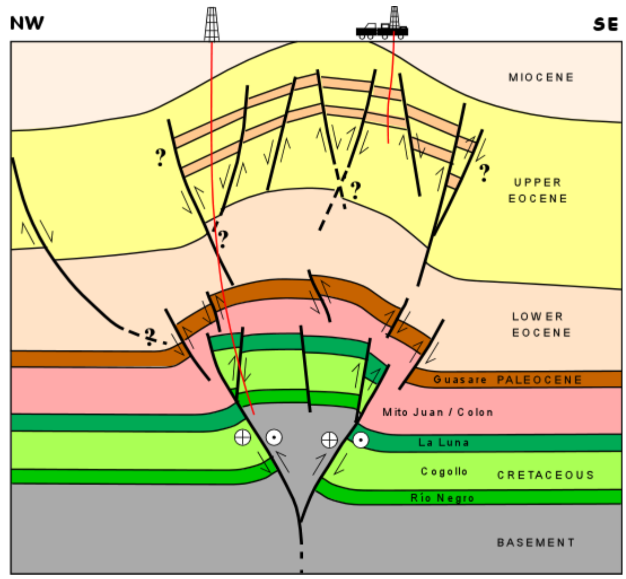


Fig.3: Schematical cross-section of the field.

Three-Dimensional Images of the Cretaceous Structures

General Trends in fault networks

The structural geology of the Cretaceous reservoir follows the regional trends observed in several oil fields in the Maracaibo basin (Nelson et al., 2000). NE-SW oriented reverse faults dominate the structural framework, forming folds as they dissipate upwards. Subordinate reverse and, in less proportion, normal faults affect the main structures. Among these faults, the NW-SE oriented normal faults are the most conspicuous. We also note the presence of pure strike-slip faulting (i.e. without vertical offset).

Three Main Structures

Because the top Socuy Member (top Cretaceous Limestones) makes a strong and continuous seismic reflection, it was chosen as a level of reference. After interpreting it, we used it to map the top of the reservoir (Cogollo Group). Interpretation of the 3D seismic on the top of the Maraca Formation reveals three main structures in the field, named "Cretaceous South", "Cretaceous North" and "Cretaceous C0152" (Fig.4).

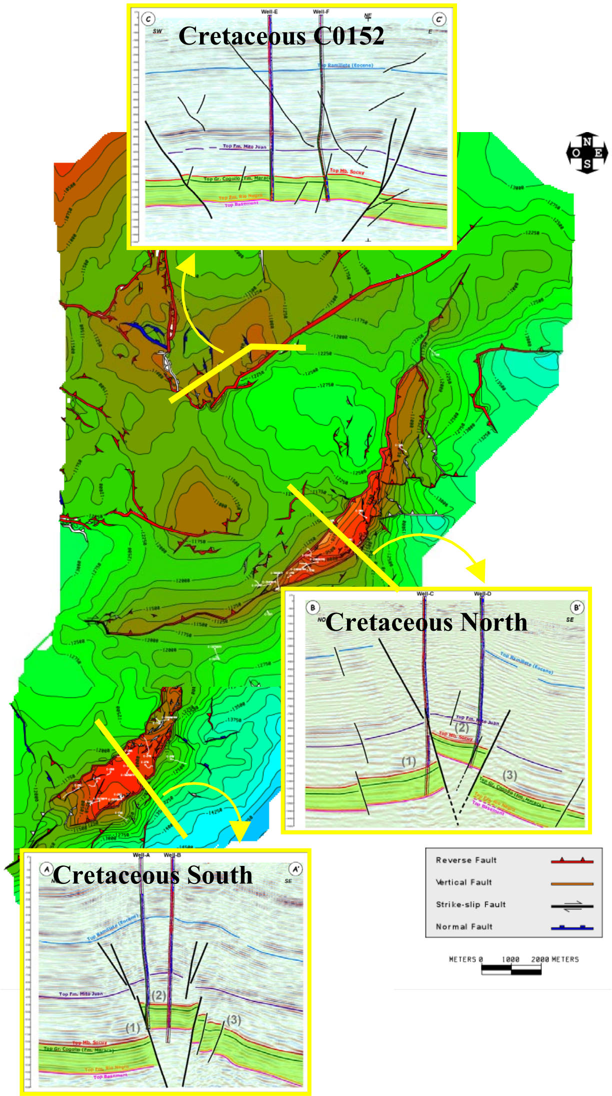


Fig.4: The three main structures. Structural map at the top reservoir (top Maraca Formation).

The "Cretaceous South" and "Cretaceous North" structures are positive flower structures (Fig.4), each of them composed by three sub-structures: (1) the NW flank dipping to the NW, (2) the central pop-up planar or dipping gently to the SE and, (3) the SE flank dipping to the SE. In map view, each central pop-up is bounded by two major opposite reverse faults (maximum throw around 2,000 ft.) which curve toward each other and get connected. This feature is especially noticeable for the "Cretaceous North" structure. Each sub-structure is affected by subsidiary faults (reverse and normal faults). These two pop-up structures are separated by a depressed area (Fig.4). In 3D, these structures evolve along strike (Fig.5). The structure presents a symmetry in which the almond-shaped central pop-up represents the axis and the two opposite flanks, the extremities, inducing an inversion of the vergence along the general strike.

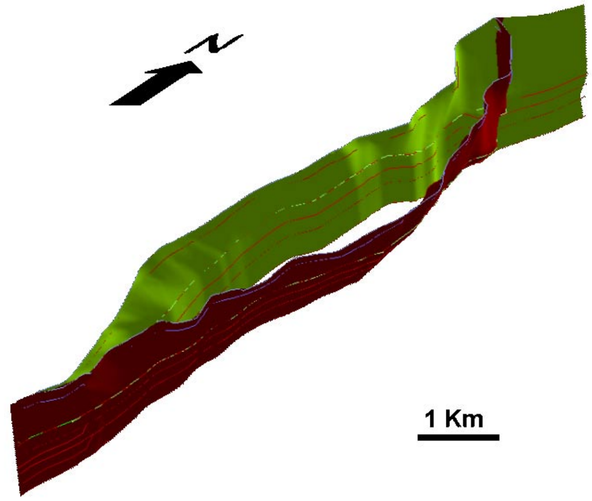


Fig.5: Three-dimensional geometry of almond-shaped pop-up structure. Cretaceous South Structure.

The "Cretaceous C0152" structure is limited to the SE by a major reverse fault, and to the west by a major strike-slip fault zone. These features define a contractional fault block (as defined by Harding 1985) dipping gently to the NNW (Fig.4). The main reverse fault displays a smaller offset (maximum throw around 1,000 ft.) than those major faults of the "Cretaceous South" and "Cretaceous North" structures. This block is affected mainly by normal secondary faults.

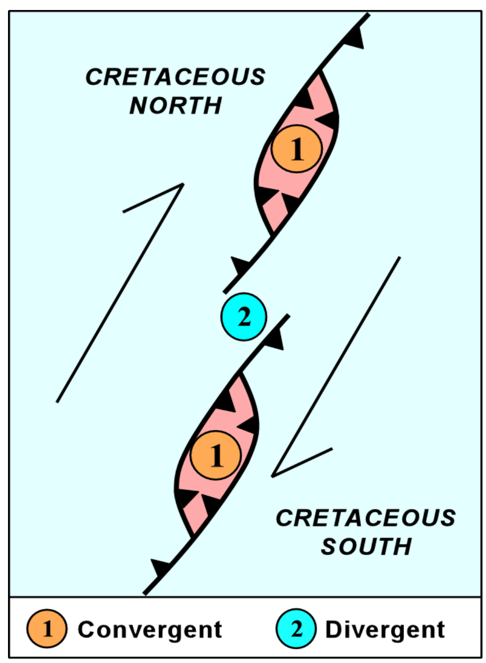


Fig.6: Structural model of La Concepción field: en échelon transpressional stepovers.

Structural Model of La Concepción Field

There is a lot of evidence that the predominant deformation, affecting the Cretaceous reservoir, was caused by a transpressional tectonic event (from wrench faulting to en-echelon faulted fold to strike slip faulting). At the Cretaceous level, main structures are represented by two major stepover zones forming two en échelon almond-shaped pop-ups (Fig.6). The individual geometry of each pop-up structure and the left stepping en échelon disposition of them suggest a right lateral strike-slip movement (Marchal *et al.,* 2002).

Fault-Associated Fracture Production

Fracture Characterization

We compiled and plotted fracture and breakout data (Marchal *et al*., 2002). This information comes from different historic sources such as Acoustic Image logs and Caliper logs. Image logs provides fracture characterization (e.g., geometry, direction, aperture) as well as breakout direction. From the Caliper log, we obtained in some cases information about the possible breakout direction.

The analysis of the direction of the open to semi-open fractures shows a dominant NW-SE orientation in most of the wells (Fig.7). Different orientation of the fractures in some wells can be linked directly to the influence of the associated fault. In this case, the resulting fracture direction parallels the fault plane strike. The comparison of the Image log with the core fracture analysis indicates that Acoustic Image logs are mainly sensitive to open and semi-open fractures. The closed ones are barely or never seen.

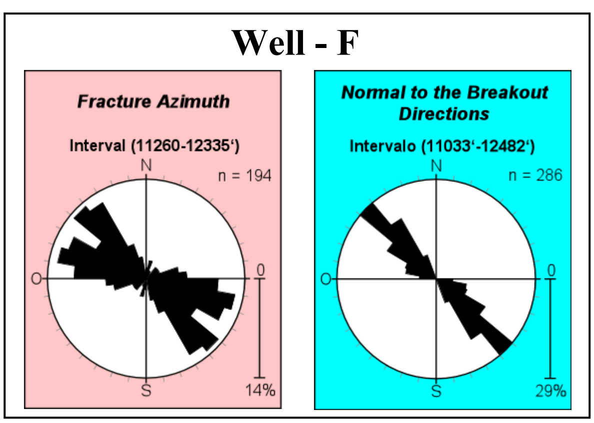


Fig.7: Open and semi-open fracture orientations and breakout directions. In general, the wells display fracture orientations and breakout directions very similar to those of well F, in the entire field.

The breakout direction analysis performed in the wells with available logs shows that the maximum borehole-perpendicular component of present-day stress is predominantly oriented NW-SE. Because this direction is predominant in the whole field, we assume that the present-day maximum principal compressive stress is oriented NE-SW (Marchal *et al.,* 2002). Regional studies indicate similar σHmax in all this part of the Maracaibo basin (Audemard & Audemard, 2002). Preliminary investigation of the World Stress Map database (Mueller *et al.,* 2000) shows that the western part of the Maracaibo basin is subjected to NE-SW extension. This observation suggests that the dominant NW-SE orientation of the open fractures in the La Concepción field may be directly linked to the direction and nature of the extensional present-day stress field acting in the Maracaibo basin. This suggested extensional present-day stress field also explain why we encountered wellbore instabilities during drilling following a NW-SE direction.

Fault-Associated Fracture Characterization

In order to delineate the relationships between faults and fracture distribution in the reservoir, we made quantitative studies using image logs and seismic data - standard seismic display (amplitude) as well as seismic attributes (e.g., coherency) (Fig.8).

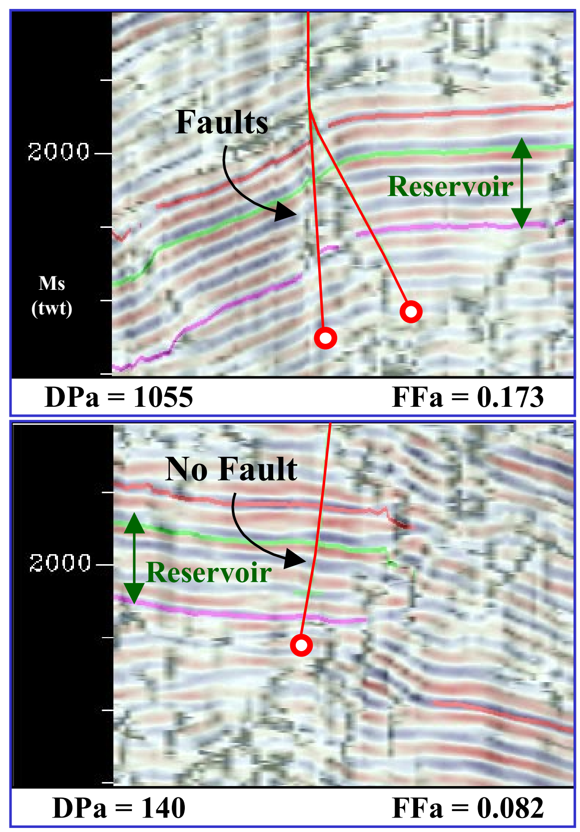


Fig.8: Fault occurrence - Fracture frequency relationship. Cross-sections mixing amplitude and coherency attribute displays. DPa: Average Daily Production (Bls/d). FFa: Average Fracture Frequency (in fract/feet).

Analysis of fracture distribution in acoustic image logs shows important clustering of fractures around faults identified with the seismic data (Fig.9). All the fault types (reverse, normal, strike-slip) seem to have a similar fracture distribution around them. We have also characterized the increase of fracture frequency approaching the fault core that is the center of the fault zone made of rocks displaying the maximum deformation.

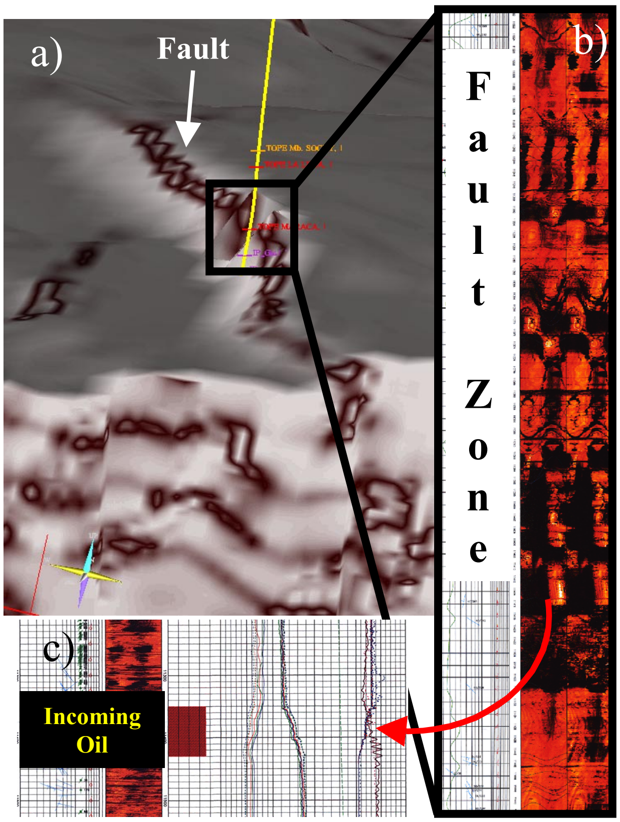


Fig.9: Fault - fracture distribution relationship. (a) Fault on a Coherency attribute map. (b) Acoustic image log showing the increasing fracture frequency towards the fault core. (c) Production log showing the clear relationship between the fault zone and the incoming oil.

As shown by the analysis of the PLT logs, these clusters of fractures constitute the best producing intervals of the wells. We have also noticed that it may exist producing intervals not related to fault-associated fractures, but with minimal contribution to the production.

Well Classification vs Build-up test responses and Fracture block systems

Analysis of Build-up tests acquired in the Cretaceous wells of the La Concepción field reveals three main type of response:

- ✓ A-type Build-up tests typically show a radial flow without testing boundaries in extended times. This kind of homogeneous response may be produced by fracture block systems classically represented by the Warren and Root conceptual model (Fig.10a).
- ✓ B-type Build-up tests display a short radial flow period followed by bilinear flow (fig.10b). This kind of behavior correspond to a well located in an almost homogeneously fractured medium (radial flow) which fluid charge control is a finite conductivity fractured medium (bilinear flow), interpreted as generated by a fault.
- ✓ C-type Build-up tests are related only to bilinear flow(s), without stabilization through time (Fig.10c). Bilinear flow is the response of unidirectional fracture system production.

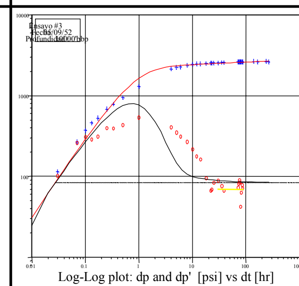
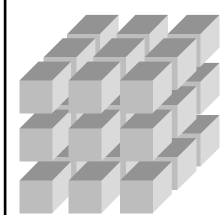
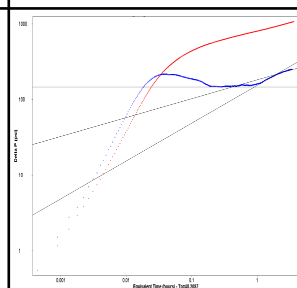
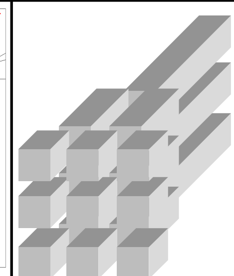
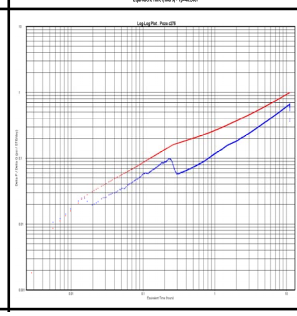
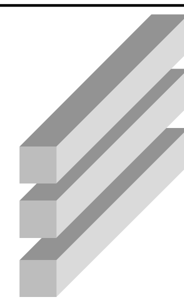
Build-up types	Build-up responses	Fracture block model
A-type		
B-type		
C-type		

Fig.10: Build-up types. Typical response and fracture block model.

These three types of flow responses are linked to the structural model of fault-associated productive fractures (Fig.11):

- ✓ Wells displaying A-type Build-up tests are related to a fault zone that produce a dense and complex fracture network.
- ✓ Wells showing B-type Build-up tests are located in a zone close to the fault zone or at the tip of the fault, in a damaged zone linked to the process zone of the fault.

- ✓ Wells presenting C-type Build-up tests are crossing background fracture systems, characterized by a poor connectivity of the fracture network.

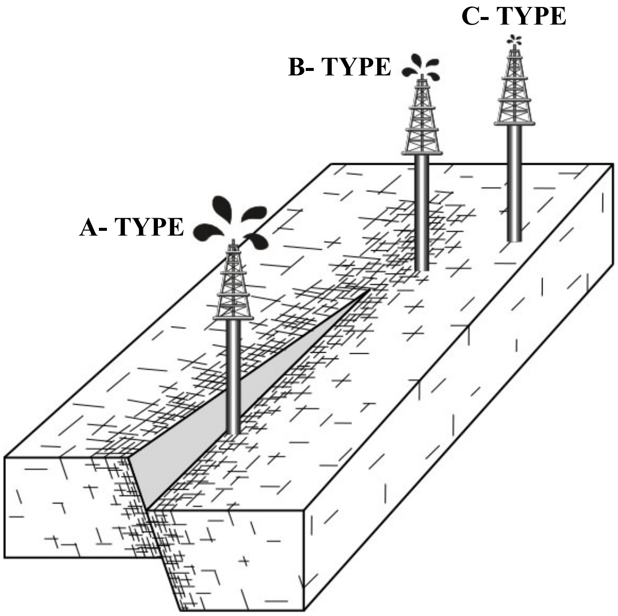


Fig.11: The spatial distribution of the permeable system developed by the fault-associated fracture system and its relationship to the production.

Conclusions

The 3D seismic interpretation allowed us to delineate the structures and draw a consistent structural model (en echelon transpressional stepover zones). Due to the strong relationship between faults and producing associated fractures, the 3D seismic allows to detect the main fracture zones by imaging the faults (e.g., coherency attribute).

Fracture clusters are the main factor for the well productivity. The main parameter controlling the fracture cluster location is the fault zone. Fracture frequency decrease away from the fault zones. Productive (open and semi-open) fracture direction is controlled by the extensive (?) present-day stress field acting in the northwestern part of the Maracaibo basin.

Build up tests typically show three types of response directly linked to the fracture block models which define the permeable system of fractured non-porous rocks. Finding and developing this permeable and producing fracture system is highly linked to the structural model of a fault with its associated damage zone and process zone.

Our main objective is to cross the fractures associated to the faults. Since the acquisition of the 3D seismic, we plan each well to cross a "seismically visible" fault in order to cross the associated fracture network. The presented exploitation model is used to expand the activities inside the developed structures and find new ones. This model is proved to be successful since it has permitted to double the daily oil production in La Concepción Field in four years.

Acknowledgments

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