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A 3D Seismic Volume of a Major Buried Thrust Front, Foredeep to Emergent Thrust Sheets, Quiriquire Block:

Platform for Improved Exploration and Production, Eastern Venezuela Basin

Summary

Sizeable 3D seismic surveys over buried thrust fronts provide the start of a full 3D work process that greatly improves the exploration and production efforts of multiple plays in complex geologic trends in order to maximize their profitability. This full 3D platform not only improves seismic imaging and interpretation, but allows continuous 3D analysis of the projects, from structural, modeling and mapping, to cost reduction efforts for well and development programs, to stratigraphic, structural, and fracture modeling input for full field simulation and in-fill drilling. For this 3D work process to effectively function and have positive impact on the E&P bottom line, it is essential that there is interaction of all disciplines throughout the project life and continuity of experienced, highly motivated team members.

Introduction

YPF/Maxus and its partners have achieved a full 3D image of a buried thrust front in one of the most prolific hydrocarbon-bearing trends in the world with two merged 3D seismic surveys totaling 550 km^2 of surface coverage (excluding overlap). This 3D volume covers a series of stacked thrust sheets, which form the eastward continuation of the Furrial Field complex in the Eastern Venezuela Basin. These data and the interpretive products were performed as a part of our technological commitment to Lagoven in the service contract of the Quiriquire Block, awarded to Maxus in the 1993 Second Marginal Field Bid Round. The technical drivers that helped determine an aggressive bid on this block were:

1. proven basin with prolific hydrocarbon charge from the world-class Tethyan Cretaceous source rock in a "cool" thrust front setting with a low geothermal gradient,
2. multiple reservoir objectives that help mitigate the increasing reservoir quality risk on this east side of the basin,
3. evidence of reasonable amounts of quartz arenite sand systems which tend to retain effective permeability with depth,
4. evidence for a continuation of the Furrial and Orocual structural trends into the block with large thrust-induced anticlines (Viboral in particular),
5. a structural model which supported well-developed 4-way closure in spite of the difficult, low-resolution 2D seismic.

The interpretation and mapping of the poorly imaged Viboral structure, in particular, was key. Many companies interpreted this structure as a continuation of the Furrial-Boqueron trend, but the depth of the first major reservoir interval and the size of the structure marked the difference between an aggressive or moderate bid. A 3D survey was part of the Maxus bid in order to help ease the concerns on reservoir target depth and the size and detailed geometry of the structural closure. Reservoir quality, however, loomed as the most serious risk and, due to the low frequency of the seismic at these great depths, only the drill bit reveals these answers.

The first survey, the Viboral 3D, was acquired in 1994 and represents one of the first exploratory 3D seismic sets in Venezuela. The second survey, the Quiriquire Norte 3D, was completed in 1997 to the north of the first survey and has both exploration and development objectives. The surveys were designed with sufficient apertures to adequately migrate and image a full interpretive view of this complex, stacked thrust front.

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Viboral 3D (Southern Survey): 1994-5, 325 km², 8-Second Record Length; Dynamite Source

The primary target of the southern survey lies in the deep Viboral thrust structure at 16,000 to 20,000 feet, into which the San Luis-Lagoven-1X discovery well was drilled in 1996, followed by the SLL-2X well this year. The survey also included a shallower secondary objective in the syntectonic Carapita sands on the backlimb of the Viboral thrust structure, in part prompted by the Cachipo wells of the 1950's which proved that the upper Carapita sands were marginally productive out of thin syntectonic sands.

Quiriquire Norte 3D (Northern Survey): 1996-7, 244 km², 7-Second Record Length; Dynamite (92%) & Vibroseis® (8%) Sources

The northern survey was much more difficult to design and acquire owing to the diversity of objectives at varying depths and the more difficult surface conditions (rugose topography, outcrops, culture, and Quiriquire Field infrastructure). Target depths range from around 2,000 to 15,000 feet. This wide range is due primarily to the stacked nature of this imbricated thrust front and our desire to include the Quiriquire Shallow Field with its post-thrust alluvial reservoir section.

Geologic Setting and 3D Survey Objectives

The principal objective section of the combined surveys ranges from greater than 18,000 feet in the south, as the target section descends into the foredeep, to the partially emergent and outcropping thrust sheets in the north which form the transition into the Serrania del Interior. This sequence of thrust sheets consists of Paleogene and Cretaceous reservoir-prone formations that ride on, or detach with, the prolific Cretaceous Querecual source rock. After the majority of the compressional deformation in the Miocene, these thrusts were rapidly buried under the sealing syntectonic Miocene Carapita, Mio-Pliocene La Pica, and the post-thrust, monoclinal Plio-Pleistocene Quiriquire Formations. This burial effectively hides the immense underlying dimensions of five major thrust sheets, which can have displacements of greater than 5,000 feet and a combined structural relief of well over 20,000 feet. To the north, the Quiriquire alluvial sequence holds the historic Quiriquire Field, a stratigraphic accumulation of nearly 4 billion barrels of oil in place, 760 MMB of which have been recovered to date (about 15° API). Under this shallow monoclinal deposit lies the Quiriquire Deep Field, a long-known productive thrust anticline in the third thrust sheet of the buried thrust front succession.

It is important to realize why this thrust front tends to develop pronounced anticlines with well-developed four-way closure. Part of this deformational pattern is due to the nature of the stratigraphic succession in this foredeep basin and the resulting fault and fold geometries. In particular, the undercompacted, ductile, and shale-prone nature of the Carapita molassic section, which was rapidly deposited over the competent pre-thrust section, has a profound effect on the hanging wall and leading-edge geometries. Thus, thrust faults in this trend are considered to ride on basal detachments in the Cretaceous Querecual or deeper shale sections, ramp through the massive sand-prone layers of the Upper Cretaceous and Paleogene, and detach into freshly deposited Miocene Carapita section. This defines large-scale flat-ramp-flat geometries that tend to form extremely well-developed anticlines with long, steep forelimbs and good structural closures. This fold style may be most pronounced in buried thrust fronts where the upper detachment levels emerge into unconsolidated, shale-prone or even starved basin settings. Thus, for this and other reasons, fault and fold style can change through time during the evolution of a thrust system, and can determine differences in the degree of trap risk and structural definition of the prospect portfolio.

3D Seismic Target Summary: Five Stacked Thrust Sheets

The entire Quiriquire-Viboral stacked imbricate thrust front affords at least five major target thrust sheets, consisting of the following sequence, from south (deep) to north (shallow):

1. Viboral thrust sheet, 16,500 to 25,000 feet,
2. Second step thrust sheet, 12,000 to 15,000 feet,
3. Quiriquire deep thrust sheet, 6,000 to 11,000 feet,
4. 509 thrust sheet, from around 4,500 to 8,000 feet and covering a smaller area
5. Northern thrust sheet, which actually consists of a series of more diversely deformed sheets and fault blocks at around 2,000 to 6,000 feet.

Each thrust sheet contains huge fold structures with 1,500 to 4,000 feet of vertical relief, 10 to 15 kilometers in length and some 3 to 6 kilometers in width. The flanks of these structures typically reach 45° angles and greater. Thus, the 3D survey designs took into account not only the necessary migration apertures, but also factored in what might be referred to as "interpretation aperture" in order to ensure sufficient lateral image of this low-angle thrust environment with the diagnostic forelimb, backlimb, footwall, hanging wall, lateral ramp and tear fault features. ➾

Examples of Exploration and Delineation Wells Based on 3D

San Luis-Lagoven-1X Well: Viboral Thrust Sheet (Actual Total Depth: 19,165 feet)

Deep Thrust Anticline

The main work commitment of the Quiriquire Block service contract for Lagoven was the drilling of the deep exploration well, SLL-1X, on the principal deep thrust anticline of Viboral, the next structure in the eastward continuation of the prolific Furrial to Boqueron trend. As one of the deepest wells in the trend, it required large amounts of pre-planning and full multi-discipline coordination, taking into account Lagoven's considerable experience. We elected to first shoot a sizable exploratory 3D seismic survey in 1994 for a number of reasons. Some of the prominent factors were:

- the original 2D seismic provided a very low-resolution image of the Viboral structure, and it was considered likely that part of the problem could be solved only with a 3D solution,
- a Well-to-3D-seismic cost ratio of greater than two,
- the apparent confirmation of moderate to good reservoir of equivalent age in all nearby fields (to the north, northwest, and west) was considered sufficiently encouraging,
- the need to optimally select the first well location in relation to the absolute crest (possible gas cap),
- the decision to stay away from the complications we might encounter with the numerous secondary faults and possible internal compartmentalization of the Viboral structure, as observed in nearby fields,
- the need to be able to quickly evaluate the results of the first well in the context of the entire prospect,
- the need to quickly select the optimal second well location based on the results of the first well.

The results of the Viboral exploration 3D survey were excellent (parameters to be given) and clearly showed the large dimensions of a thrust anticline with nearly 4,000 feet of closure. A comparison between the original 2D and the 3D seismic illustrates remarkable improvement. With a high-quality 3D data set, it was possible to be selective in terms of these and other location criteria.

Not only is the crest and classic fault bend fold feature clearly imaged, but the steep forelimb, internal faults and fold geometry, lateral ramps, tear faults, footwall, and even the subthrust segments are all exceptionally imaged, especially considering the depth and the resulting low frequency of the data. The quality of the 3D data also provided a way to continuously "view" the drilling progress in the troublesome overlying La Pica and Carapita section, especially with the critical casing points near the top and base of overpressure (10,300 and 16,500 feet [MD] in the first well). Detailed analysis and treatment of the 3D seismic velocities helped provide accurate depth prognoses, casing depths, and contingency plans.

The second well, San Luis-Lagoven-2X, is currently being drilled. Greatly aided by the 3D data, this second well was positioned at a structural level in context with the results of the first well and on the basis of 3D cumulative dilational strain modeling, which will allow a contingency high-angle borehole to optimally intersect the predicted fracture sets for improved effective permeability.

Cachipo-6X Well: Overlying Backlimb of "Viboral Thrust Sheet" (Actual Total Depth: 16,077 feet [MD]) Syntectonic Carapita Play

The second well commitment of the Quiriquire service contract was the Cachipo-6X well, which targeted seismic amplitudes within the 3D volume in the syntectonic Miocene Carapita section over the backlimb of the Viboral thrust anticline. The general nature of this play is considered to be a deeper analogue to the proven play-types in the trend, which can be described as stratigraphic accumulations within small piggy-back sub-basins on the backlimbs of the underlying thrust anticlines. The prospect concept was that these amplitudes were sand-prone units of several thousand feet which were laid down within an extensional

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slump block above Viboral's backlimb as the unconsolidated syntectonic sediments rotated and collapsed during the growth of the thrust anticline. The Cachipo wells, which were drilled into the shallower Carapita level during the 1950s, proved that some of these types of sands had been charged with light oil. The results of the Cachipo-6X well showed a predominance of siltstone, with insufficient reservoir quality sandstone.

Tropical-1X Well: "Second Step Thrust Sheet" (Planned Total Depth: 14,865 feet [MD]) "Hidden" Imbricate Thrust Sheets

One of the immediate results of the Quiriquire Norte 3D, even with its fast-track version, was the imaging of a hidden imbricate on the "Second Step Thrust Sheet" which the previous 2D seismic survey had not succeeded in resolving. Even with the new 3D data in mind, it is difficult to pick out the position and geometry of this extra thrust imbricate on the 2D seismic. The 2D seismic data show only a "smeared" image of these overlapping sheets and does not resolve the top of the principal thrust sheet as it "disappears" under the overlying imbricate. Thus, the 2D data show only a small structure with regional dip. The 3D data, however, clearly show that this structure continues under the upper imbricate, thereby gaining considerable structural relief. This difference in structural interpretation is significant because the prospect increases from a few hundred feet to 1,500 feet of structural closure with a four-fold increase in area. This prospect is scheduled to be drilled by the Tropical-1X well this year.

QQ-685: Delineation Well of the Quiriquire Deep Oil Rim with a Follow-up Horizontal Well (Planned Total Depths: 10,300 [MD] feet +2000-foot Horizontal Leg)

The Quiriquire Deep Field was discovered below the stratigraphic Quiriquire Shallow Field in 1952 with a gas blowout that later proved to be part of a gas column of around 2900 feet with an additional 500 to 700+ feet of oil rim under the gas. With the 3D control, the QQ-685 well will target this oil rim, offsetting the prolific QQ-676 well. Although the oil column is relatively thick, the steep flanks of the anticline make the 100-foot-thick Oligocene Los Jabillos reservoir a difficult target. After gaining the necessary structural and stratigraphic control from a vertical pilot hole, a separate well will be drilled with a 2000-foot horizontal leg through the 100-foot-thick Oligocene reservoir, parallel to the oil/water contact. Once positive results are obtained from the QQ-685 well, further development wells and a gas cycling project will follow.

3D Platform and Multi-Discipline Team Aspects: Risk Assessment and Optimization of Complex Projects

One of the principal benefits of this sizeable 3D seismic volume is that it established a platform from which many other aspects and disciplines could continue to evolve in a 3D framework, including:

- 3D structural modeling and mapping, fracture/strain modeling, and a basis for improved 2D modeling,
- 3D stratigraphic database and eventual modeling to provide a link to the reservoir simulations,
- 3D borehole planning, high-angle and horizontal drilling with real-time adjustments,
- 3D reservoir simulation with fewer restrictions and easier model preparation for sector and full field simulations, which can then be carried on into secondary recovery, gas cycling, and in-fill drilling.

It is essential that there is continuous interaction of all disciplines and individual team members for this 3D work process to properly function and maximize the profitability of these complex geologic trends.

Technical Risks: Reservoir Quality and Hydrocarbon Phase

Because of the extremely favorable petroleum system in the Eastern Venezuela Basin and the large size of the thrust structures (1,500-4,000 foot closures, perhaps filled to spill), the most serious technical risk is reservoir quality. The other important prospect risk is the hydrocarbon phase, which varies considerably throughout the trend from gas ➜

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condensate, to volatile oil, medium-gravity undersaturated oil and heavy oil to even tar. Tar mats can occur not only due to biodegradation, but also owing to asphaltene drop-out at great depths. In many cases, of course, the hydrocarbon phase and reservoir risks are intimately coupled because, for example, some low-quality reservoirs produce due to the high mobility ratio of that structure's unique hydrocarbon phase and high reservoir pressures, whereas in other structures, better quality reservoirs fail to effectively produce owing to somewhat heavier gravity crudes. Our evaluation and approach to the reservoir risk is considered to be one of the most challenging technical problems we face in the frontier areas of the Eastern Basin and as deeper and more subthrust plays are pursued throughout the basin. Solutions with respect to reservoir risks are likely to include:

- Finding technology that increasingly improves the seismic resolution in order to enable more accurate stratigraphic prediction. This includes understanding the regional stratigraphic framework, especially for predicting the depositional trends of quartz arenite systems which maintain highly efficient pore networks even in the low-porosity ranges of 4 to 10% (most recently O'Leary et. al., 1997, *Simposio Bolivariano*, Memorias Tomo I, p. 163-6).
- Understanding reservoir characteristics via modeling of the depositional geometries, petrography, fluid inclusions, fractures, and the timing of cementation. This information can bring to light ways of enhancing reservoir performance, including making use of natural fractures by successfully predicting fracture orientation, density, aperture, and effective permeability ranges.
- Implementing drilling and completion techniques that minimize the formation damage of low-permeability reservoirs and optimize artificial fracturing techniques, perhaps in combination with the natural fractures.
- Optimizing techniques to reduce production limitations owing to such things as condensate banking, reservoir pressure and fluid viscosity limitations, and hydrocarbon phase complications such as asphaltene flocculation.

Conclusions

The 550 km^2 combined Quiriquire-Viboral 3D seismic volume provides coverage over an entire buried thrust front and is one of the first in what we believe will be an industry trend to increasingly use 3D technology to optimize the exploration and development of complex geologic trends. Rather than yielding an image of a single structure, this 3D volume provides a unique, continuous view of the geometry and development of stacked and buried thrust fronts, from the deep thrust anticlines encroaching the foredeep to the highly elevated and partially eroded emergent thrust sheets that form the outer ramparts of the Serrania del Interior. The huge 1,500 to 4,000-foot thrust structures form a stacked imbricate sequence of Paleogene and Cretaceous reservoir-prone section, underlain by world-class Cretaceous Querecual source rock and draped by excellent Miocene Carapita seal, all of which provide the economic incentive to undertake such extensive 3D efforts. Reservoir quality looms as the most serious threat to the successful outcome of projects in this trend. In tandem with reservoir quality, hydrocarbon phase can also be a limiting factor. Finding solutions and achieving success in regard to reservoir quality is one of industry's greatest challenges as the proven reservoir systems are pursued into the less known areas. Optimum success will depend upon our industry's ability to deal with low-porosity and fracture-enhanced reservoir systems. Thus, it is even more critical that the other technical risks, such as structural definition, are efficiently assessed by using advanced concepts within a robust 3D framework.

The Quiriquire-Viboral 3D seismic volume acquired over this Eastern Venezuela buried thrust front allows continuous 3D treatment and analysis of the projects, from structural and stratigraphic modeling to drilling and reservoir simulation. Thus, the 3D platform is not only for structural interpretation and visualization, but also 3D fracture/strain analysis, stratigraphic modeling, borehole planning—including high-angle and horizontal drilling—on-the-fly adjustments while drilling, well and prospect evaluation, reservoir simulation, early and optimum reservoir pressure maintenance programs, and finally, secondary sweep programs with in-fill drilling. The benefits include more accurate well planning and drilling programs that provide one of the best ways to reduce individual well and total development costs, while minimizing the chances of missing productive fault compartments, especially in the case of "hidden" low-angle imbricates. This becomes even more critical when facing complex fluid phase changes and thin oil rims which demand precise imaging, targeting, drilling, and evaluation.

The scope and economic implications of these complex projects require a realistic understanding of how all this must fit together into seamless project phases in which continuous interaction of all disciplines and the individual team members throughout the course of these projects is essential. We trust that the results of the Quiriquire-Viboral project, with continued full implementation of this team process, will have important implications for the future exploration and production efforts in the Eastern Venezuela Basin, especially in its more frontier areas such as to the east in Guarapiche and in the progressively deeper and subthrust positions throughout the basin.

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Biographical Sketch

Vincent Rigatti is an exploration coordinator and senior geophysicist for Maxus Venezuela in Dallas, Texas. He has been employed with Maxus/YPF/Diamond Shamrock for 14 years. He has worked in Dallas, Jakarta, Midland, and Amarillo, and during that time he has worked many of the basins in southeast Asia and the continental U.S. Previously, he worked for Getty Oil Co. He received a B.S. degree in geology/geophysics from the University of Connecticut in 1981. His technical interests are in seismic imaging in difficult/complex trends, 3D interpretation/ mapping, and visualization. ❑