STRATIGRAPHIC ANATOMY OF SHELFAL MIOCENE RESERVOIRS: WESTERN MATURÍN BASIN, VENEZUELA

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SUMMARY

The Maturín basin is a supercharged hydrocarbon setting that hosts the world's largest individual oil accumulation: the Orinoco Belt, *in situ* 1.2 TBO. Miocene strata represent the most prolific reservoirs in the Maturín and in several of the Eastern Venezuela-Trinidad oil districts. Production in this region is in excess of 10 BBO. In spite of protracted and intense exploration and production activity by the oil industry, detailed stratigraphic knowledge on the oil-bearing Miocene successions has received only limited consideration in the public domain literature. As part of a field reactivation project undertaken on behalf of Corpoven S.A., rightholder of the Quiamare-La Ceiba unit (Fig. 1), the Lower-Middle Miocene succession in NE Anzoátegui was analyzed from a sequence-stratigraphic and reservoir-characterization perspective. The study follows a four-fold approach: the first part outlines the geodynamic context and describes the key elements of the basin-scale Miocene stratigraphy and paleogeography; the second part discusses the sequence stratigraphy of the 4,000 m (12,000 ft) thick Miocene series over the SW fringe of the Maturín fold-thrust belt, as well as the implications of the regional stratal patterns and facies architecture for trapping potential; the third part examines the anatomy of individual reservoirs at the parasequence scale, describes the effects of fourth-order sequences on trapping, and analyzes internal reservoir facies heterogeneities; the last part focuses on the potential of seismic inversion for pre-drill reservoir prediction and efficient development planning.

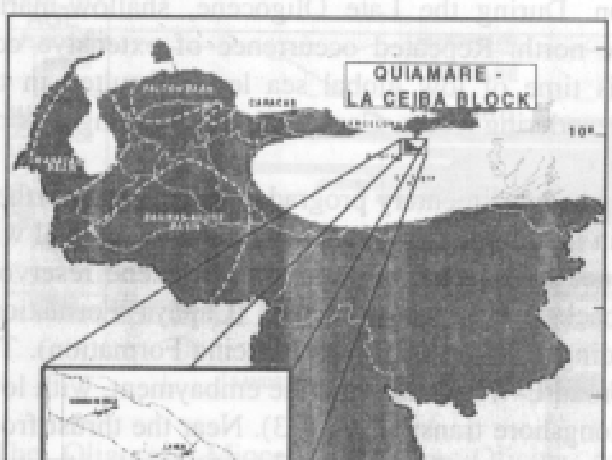

Figure 1. Location map of the area of this study and the Eastern Venezuela Basin.

THE REGIONAL CONTEXT:

Filling a Foredeep Behind the Transpressionally Impinged Northern Edge of the South American Plate.

The development of the Miocene Eastern Venezuela basin occurred in a tectonically active collage deformed after transpressional-convergent interaction of the oceanic Caribbean plate and the northern margin of the continental South American slab (Burke, 1988; Pindell, 1993; Russo and Speed, 1994). The easterly encroaching Caribbean plate induced Neogene (35-10 Ma) oblique collision (drag) and juxtaposition of allochthonous blocks. Downflexing of the northern South American craton promoted the formation of a perisutural foredeep (Bally and Snelson, 1980), and the development of a foreland basin system (Erikson and Pindell, 1993), (Fig. 2).

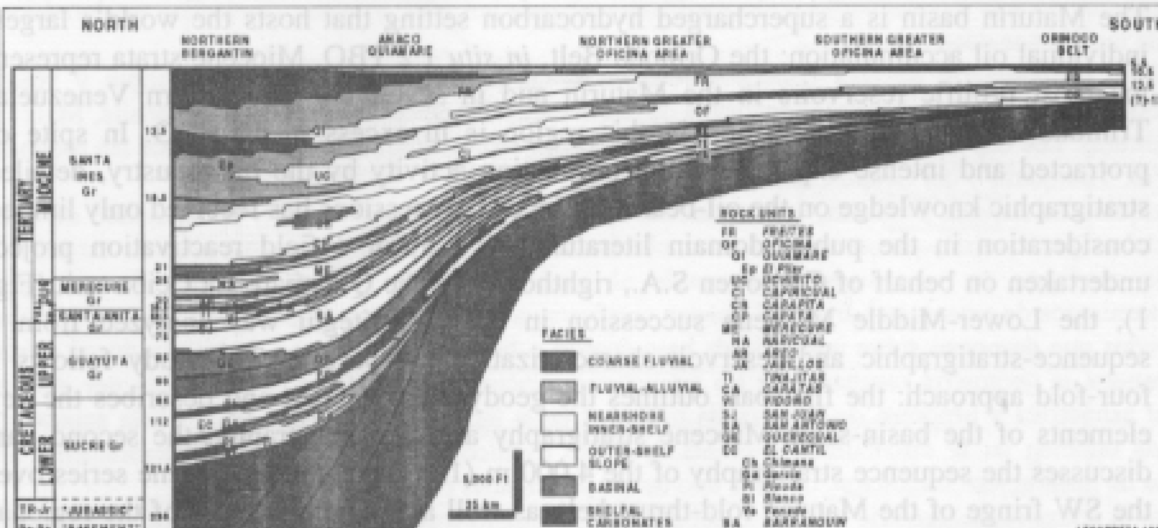

Figure 2. N-S oriented stratigraphic chart of the Eastern Venezuela Basin. The stratigraphy of the area of this study corresponds to the Anaco-Quiamare region. Ages assigned to major discontinuities are based on published dates and inferred correlation with the cycle-chart of Haq et al. (1978).

The paleo-Orinoco river, funneling terrigenous debris, principally dictated sedimentation patterns within the foreland depression. During the Late Oligocene, shallow-marine deposition was areally restricted to the north. Repeated occurrence of extensive coal measures (Merecure Formation), at this time of low global sea level, resulted in the presence of large mires, swamps, and meandering rivers. Conceivably the setting was not unlike the present Amacuro delta complex.

The Early Miocene was marked by extensive sedimentary progradation onto the northern South American hinterland. Expansion in the magnitude of coastal onlap was coeval with a sharp increase in the rate of subsidence and global eustatic rise. Miocene reservoir-prone strata are contained within a backstepping basal wedge (Capaya Formation), followed by an aggradational to prograding shelfal succession (Oficina Formation). The paleogeographic setting consisted of a broad E-W trending marine embayment, with low-relief shelfal embankments, shaped by longshore transport (Fig. 3). Near the thrust front, intra-Miocene unconformities document southerly syndepositional structural development, and a distinct foredeep is demonstrated by thick, and locally organic-rich, shales (Carapita Formation) bearing turbidite accumulations (Chapapotal Formation), (Fig. 3). By the Middle Miocene, drainage fed from the Araya-Paria area to the north and the ramp-supported uplifts in the fold belt, caused southerly and westerly progradation of sand-prone facies (Uchirito and Freites Formations).

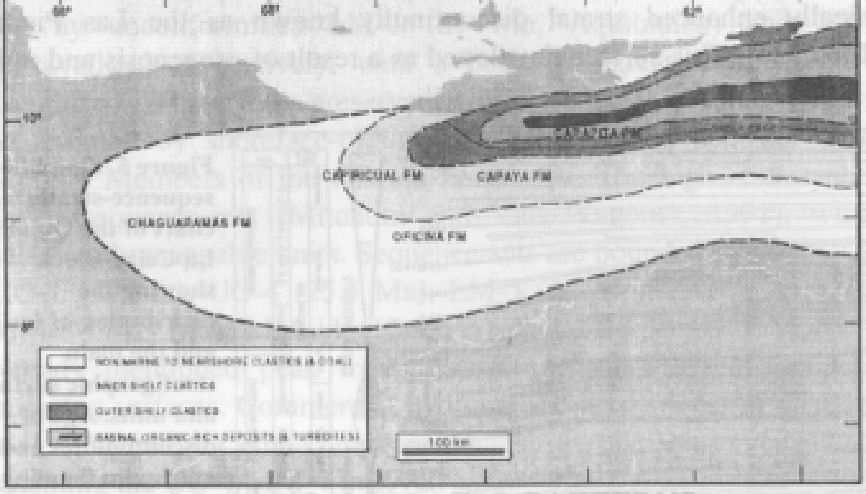

Figure 3. Generalized Early-Middle Miocene paleogeography of the Oriental Basin. Shelf break taken from Di Croce (1995).

THE LOCAL MIOCENE STRATAL PATTERNS:

Development of a 4 Km-Thick Transgressive-Regressive Facies-Cycle Wedge in a Low Latitude Clastic Shelf.

The stratigraphy of the Miocene succession within the Quiamare-La Ceiba Unit, a 1600 km^2 tract located on the western edge of the Maturín fold-thrust belt, was specifically investigated using an extensive data set which included 600 Km of 2D seismic sections, an heterogeneous suite of wireline logs from 96 wells, core and cuttings descriptions, and limited biostratigraphic data (Galeazzi *et al.*, 1996). The Oligocene-Miocene interval at Quiamare-La Ceiba is a 3 to 6 Km-thick wedge shaped succession deposited in a coastal to shallow marine siliciclastic platform. It records the deposition of a single 20 Ma-long facies cycle wedge (Fig. 4). The series records gradual northerly thickening but is dominated by a remarkably parallel stratal-stacking pattern.

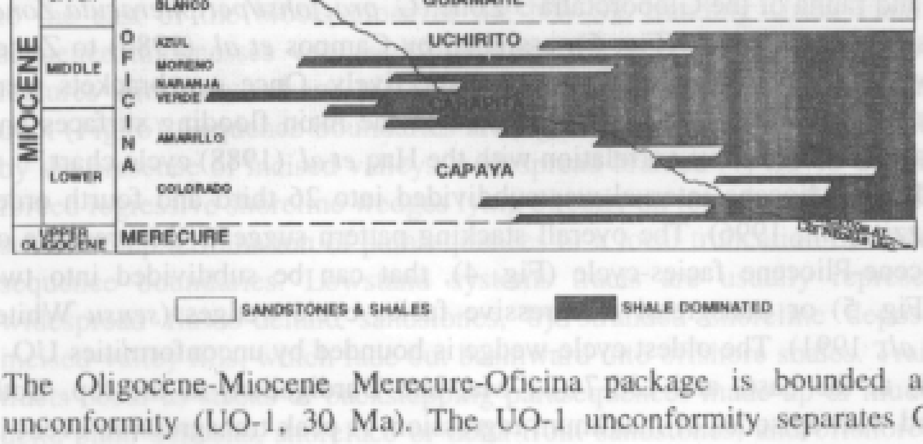

Figure 4. Simplified lithostratigraphy of the Oligocene-Pliocene interval in the Quiamare-La Ceiba Block. Note that the Oligocene-Pliocene succession records a single 20 Ma long transgressive-regressive facies-cycle wedge.

The Oligocene-Miocene Merecure-Oficina package is bounded at its base by an unconformity (UO-1, 30 Ma). The UO-1 unconformity separates Oligocene offshore shales of the Caratas Formation from the Upper Oligocene braided-river deposits and coal measures of the Merecure Formation. On top of the Merecure Formation, the Miocene succession consists of strand-plain to marine deposits of the Oficina Formation (Capaya-Carapita-Uchirito-Quiamare *eq.*, Fig. 4). The top boundary of the Oligocene-Miocene package is a tectonically enhanced stratal discontinuity known as the Las Piedras Unconformity (Mio-Pliocene). This surface developed as a result of orogenesis and uplift and locally truncates Tertiary strata.

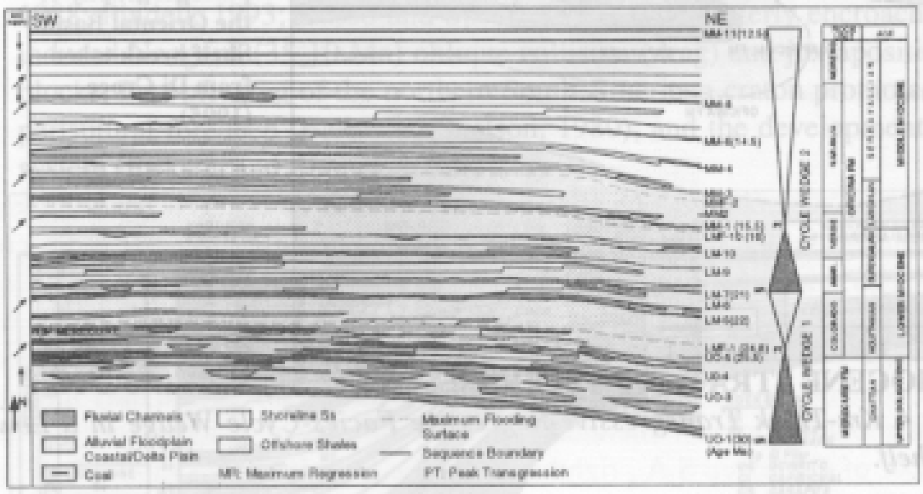

Figure 5. Simplified sequence-stratigraphic chart of the Quiamare-La Ceiba Block showing the distribution of facies, and the main stratigraphic surfaces and units. Age of discontinuities and maximum flooding surfaces are after correlation with the cycle-chart of Haq et al. (1978).

The sequence stratigraphic interpretation is based on the recognition and mapping of sequence boundaries and maximum flooding surfaces, interpreted according to stratal and reflection termination patterns, and facies stacking patterns defined by parasequence correlation of well-log cross sections and seismic interpretation. Facies of most parasequences were afterwards mapped in order to determine the block-wide distribution of Miocene reservoirs. Scarce biostratigraphic data with chronologic significance from three wells were used to age-date middle Oficina and Carapita strata as Early-Middle Miocene (N4-N12 bison range). The Merecure, lowermost and uppermost Oficina members are locally barren of age-diagnostic fauna, and they were dated based on regional correlations and published ages (González de Juana *et al.*, 1980; Campos *et al.*, 1985; Di Croce, 1995). Biostratigraphic data include *Catapsydrax cf. dissimilis* within Sequences LM6 and LM7; *Praeorbulina transitoria*, and *Globigerinoides sicanus,* within Sequence MM1; and fauna of the Globorotalia 3 Zone (*G. praefohsi/peripheracuta Zone)* within Sequences MM2 and MM3 (Fig. 5); assigned by Campos *et al.* (1985) to Zones upper N4 and lower N5, N7-N9, and N10-N12 respectively. Once age brackets were assigned to the main packages, ages were attributed to the main flooding surfaces and unconformities based on a tentative correlation with the Haq *et al.* (1988) cycle chart.

The Oligocene-Middle Miocene interval was subdivided into 26 third and fourth order sequences (Galeazzi *et al.*, 1996). The overall stacking pattern suggests the presence of one major Oligocene-Pliocene facies-cycle (Fig. 4), that can be subdivided into two megasequences (Fig. 5) or transgressive-regressive facies cycle-wedges (*sensu* White, 1980; and Vail *et al.*, 1991). The oldest cycle-wedge is bounded by unconformities UO-1 (30 Ma, Chattian) at the base, and LM-7 (21 Ma, late Burdigalian) at the top. Both surfaces are related with episodes of maximum regression. A peak transgression event is defined by maximum flooding surface LMF-1 (dated at 24.8 Ma, early Aquitanian). Cycle-wedge I is about 1,200 m-thick and consists of fluvial and fluvio-deltaic deposits of the Merecure Formation, overlain by strandline-deltaic to fully marine strata of the Colorado Member of the Oficina Formation. Cycle-wedge II is bounded at its base and top by unconformities LM-7 (21 Ma, Aquitanian) and MM-13 (10.5 Ma, late Serravallian) respectively, with a peak transgression recorded at LMF-10 (16 Ma, Langhian). Where fully preserved, Cycle-wedge II is some 3,600 m-thick, being mostly represented by shoreface-offshore to coastal-plain deposits of the Amarillo through Moreno Members of the Oficina Formation. The high-rank cycles have been split into seven sequence-sets (Mitchum and Van Wagoner, 1991), which provide consistent seismically mappable units. Sequence-sets are bounded by distinct unconformities labeled UO-1 (30 Ma), UO-4 (25.5 Ma), LM-5 (22 Ma), LM-7 (21 Ma), MM-1 (15.5 Ma ?), MM-6 (14.5 Ma), MM-11 (12.5 Ma), and MM-13 (10.5 Ma, Fig. 5). In addition, the already mentioned peak transgression surfaces LMF-1 and LMF-10 provide useful mapping surfaces. Commercial hydrocarbon occurrences in the Quiamare-La Ceiba Unit, at La Vieja-La Ceiba-Quiamare Fields, involve some 60 individual sand packages spanning the UO-1/MM-4 interval.

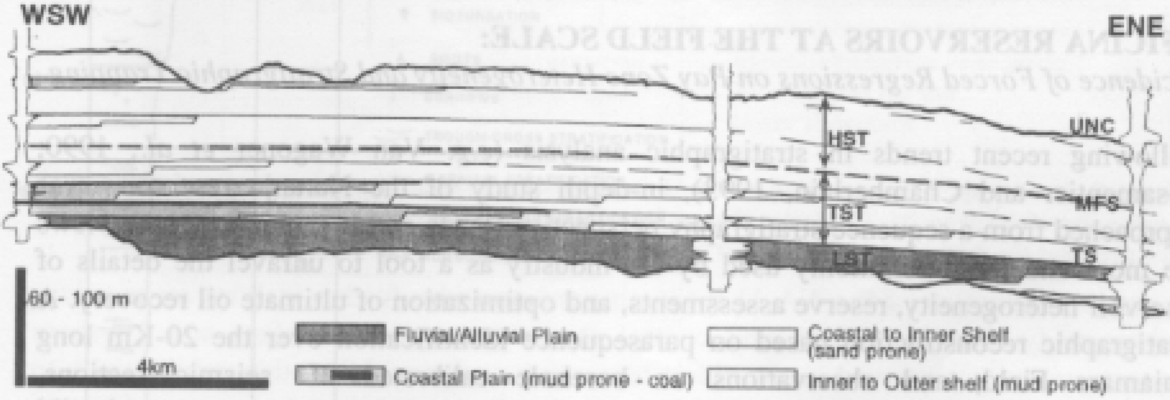

Figure 6. Sequence architecture of the Early and Middle Miocene succession, in the Quiamare-La Ceiba block. See discussion in text.

Throughout the studied interval, sequence architecture (Fig. 6) reflects a low-relief shallow water depositional setting. However, several indicators hint that during most of the Early-Middle Miocene (*circa* 25-13 Ma), the shelf to basin transition was located just to the east of the block, close to the NW-SE trending Urica Fault Zone. Individual sequence thicknesses vary within the 60-200 m range. Typical sequence development features thin lowstand and highstand systems tracts, and a thicker transgressive systems tract (Fig. 6). Sequence boundaries are signaled by facies stacking patterns characterized by the presence of incised valleys, widespread braided (?) fluvio-deltaic sand-sheets, and forced regressive shoreline wedges lying directly on top of shelfal shales. In a few cases, a subtle onlap termination of parasequences or a local truncation of underlying strata mark sequence boundaries. Lowstand systems tracts are usually represented by thin but widespread fluvio-deltaic sandstones, by stranded shoreline deposits, or by fluvial incised-valley fills, which fade out basinward into offshore shales. Transgressive systems tracts occur as stacks of backstepping parasequences made up of muddy coastal-plain or delta-plain deposits, shoreface or delta-front sandstones, and offshore shales. Highstand deposits show similar parasequence-style development (Fig. 6). They stand out as coal bearing delta-plain accumulations in the upper Merecure, but throughout the Miocene Oficina interval highstand systems tracts are thin and shale-prone, and consist of distal inner neritic sandstones or offshore shales. Our observations indicate that delta-front and shoreface sandstones of transgressive systems tracts, and braided/ fluvio-deltaic lowstand systems tracts in the Oficina Formation preferentially host oil pools. Abundant braided and distributary fluvial sandstones provide the best reservoirs within Merecure Formation. Facies maps of selected Oficina parasequences consistently show NW-SE oriented facies belts, with a prominent facies change from shoreline sandstones to offshore shales in a NE direction, as demonstrated early in the development of the area (Pyre and Manger, 1941; Hedberg and Pyre, 1944; Renz *et al.*, 1958). Consequently reservoirs terminate to the NE, associated with the shale out of shoreline sandstones. The NW-SE oriented depositional strike runs at a high angle to the E-NE oriented structural grain prevailing in the block, and in consequence provides a stratigraphic component for combination trapping across west-plunging anticlines and structural noses (Galeazzi *et al.*, 1996). Perhaps 70% of the recoverable reserves in the Quiamare-La Ceiba Unit can be attributed to these trapping configurations.

OFICINA RESERVOIRS AT THE FIELD SCALE:
Incidence of Forced Regressions on Pay Zone Heterogeneity and Stratigraphic Trapping.

Following recent trends in stratigraphic analysis (*e.g.* Van Wagoner *et al.*, 1990; Posamentier and Chamberlain, 1993), in-depth study of the Naranja reservoirs was approached from a sequence stratigraphy perspective (Porta and Risi, 1997). These views are more and more commonly used by the industry as a tool to unravel the details of reservoir heterogeneity, reserve assessments, and optimization of ultimate oil recovery. A stratigraphic reconstruction based on parasequence identification over the 20-Km long Quiamare Field, and observations on borehole calibrated 2D seismic sections, demonstrate substantial lateral continuity, prevalently parallel stratal patterns and mild depositional slopes.

The Middle Miocene (Serravallian?) Naranja hydrocarbon-bearing zones of the Oficina Formation at Quiamare Field consist of a series of partially overlapping sandstone members, the NA-L1, NA-K2, NA-J4, and NA-I reservoirs (contained within the MM-3 to MM-5 sequence interval), that alternate with 30 to 100 m-thick shale beds. The base of the sand-rich complexes is made up of lower very-fine sandstones and siltstones with wave ripples, which are bioturbated and interbedded with claystones. These facies are interpreted as lower shoreface to transition-offshore deposits. They are followed by fine sandstones with hummocky cross-stratification to parallel stratification, with rip-up clasts occasionally found at the base of the strata. These facies show the strong incidence of waves and they are interpreted as lower-shoreface accumulations. In turn, lower shoreface deposits are sharply overlain by very fine to medium sandstones with trough cross-stratification, which are interpreted as upper shoreface deposits. The upper shoreface facies are topped by very fine to medium sandstones with swash cross-stratification, interpreted as foreshore deposits. Commonly, the foreshore beds are rooted and covered by a thin coal zone. The coals are finally overlain by a thin veneer of rip-up clasts, which represents a transgressive lag. In summary, observations on cores and wireline-logs reveal that the Naranja reservoir zones were deposited in a strand zone to marine shelf setting, and were subjected to transgressive-regressive processes (Fig. 7).

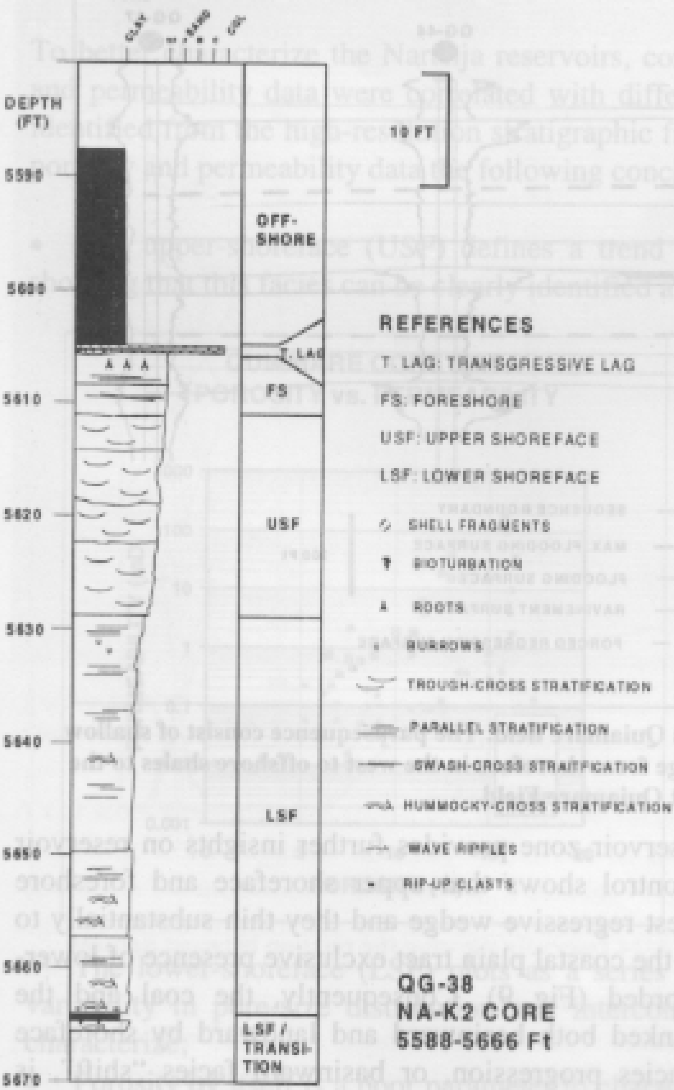

Figure 7. Detailed description of NA-K2 parasequence from cores on well QG-38. These shallow marine siliciclastic deposits records a gradual upward shallowing trend interpreted as a product of basinward progradation.

Thus, the NA-L1 through NA-I reservoir package was interpreted as a succession of ramp deposits arranged in a dominantly progradational stacking mode. Clearly, the Naranja sands step basinward in an East-Northeast direction. The oil-bearing genetic packages are 30 to 60 ft thick, and they are internally organized as sand-rich coastal plain-shoreface deposits prograding into offshore shelfal shales (Campos *et al.*, 1985). Each of these coastal-plain to shallow marine siliciclastic units documents episodes of shallowing and sand encroachment, recorded by upward-coarsening and -thickening trends. The pattern is interpreted as the product of coastal progradation during periods of relative sea-level stillstand, or as a result of high-rate sediment supply relative to accommodation potential. From a practical standpoint, the Naranja depositional packages at Quiamare record a facies spectrum from reservoir-prone towards the W-SW to non-reservoir towards the E-

NE end of the field (Fig. 8). When superimposed on an easterly plunging anticline, this stratal pattern provides a critical stratigraphic component to oil trapping.

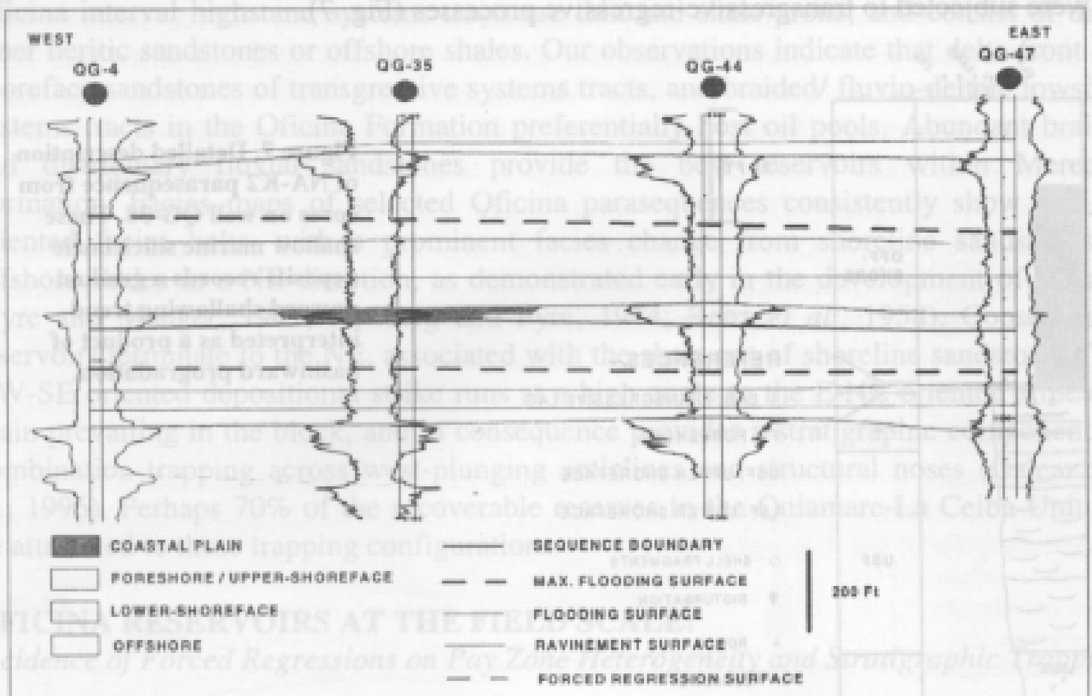

Figure 8. Stratigraphic cross-section across Quiamare field. The parasequence consist of shallow marine shoreface deposits. The facies change from shoreface in the west to offshore shales to the east provides the critical trap component at Quiamare Field.

A close examination of the NA-J4 reservoir zone provides further insights on reservoir heterogeneity. Closely spaced well control shows that upper shoreface and foreshore deposits are only preserved in the oldest regressive wedge and they thin substantially to the east. On wells located landward of the coastal plain tract exclusive presence of lower- and upper-shoreface facies was recorded (Fig 9). Consequently, the coal and the associated coastal plain facies are flanked both basinward and landward by shoreface deposits. This discontinuity of the facies progression, or basinward facies "shift", is interpreted as the result of a forced regression (Posamentier *et al.*, 1992). At the field scale these forced regressive patterns create significant permeability barriers that influence individual well performance, and demand adjustment of ideal well spacing.

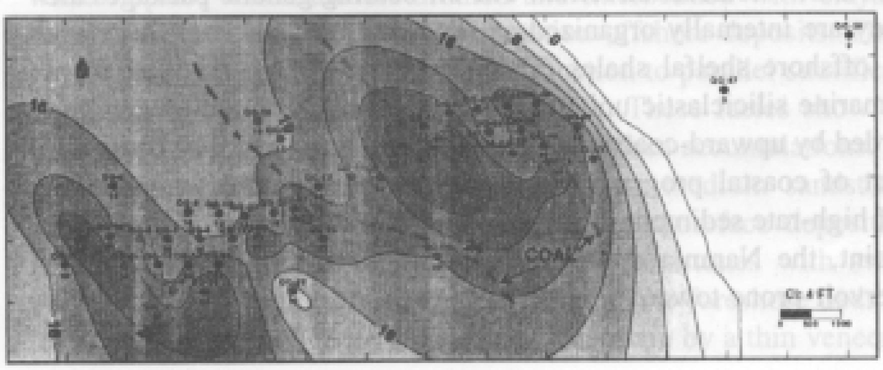

Figure 9. Isopach map of upper shoreface plus coastal plain facies combined with the coal distribution for the NA-J4 reservoir. The coal deposits are flanked basinward and landward by shoreface facies; this facies shift is interpreted as the results of a forced regression.

Role of facies architecture in reservoir properties and natural fracture distribution.

To better characterize the Naranja reservoirs, core and core-calibrated wireline porosity and permeability data were correlated with different rock types and facies associations identified from the high-resolution stratigraphic framework. After plotting in conjunction porosity and permeability data the following conclusions were driven:

- The upper-shoreface (USF) defines a trend that follows closely a regression line, showing that this facies can be clearly identified and characterized (Fig.10);

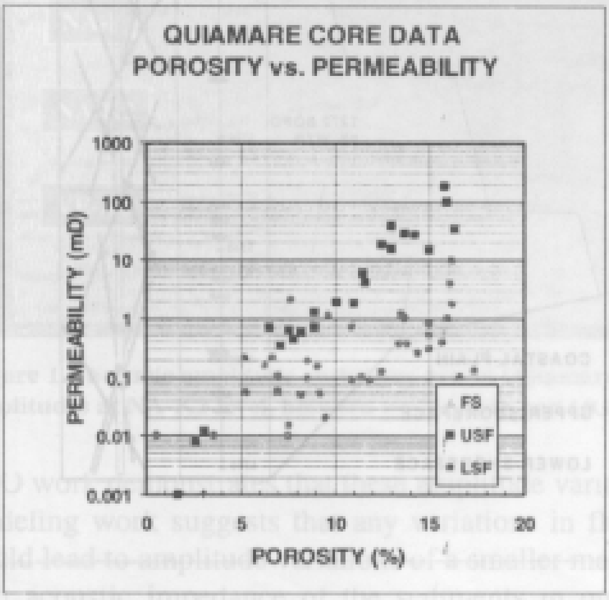

Figure 10. Core porosity / permeability cross-plot of Quiamare Field. The upper shore-face parameters follow a regression line, opposite behavior can be observed for the lower shoreface facies.

- The lower-shoreface (LSF) plots as a series of scattered values, reflecting random variability in pore-size distribution and interconnection: LSF deposits are difficult to characterize;
- Porosity by itself is a poor parameter to characterize these reservoirs. In wells lacking porosity logs, the SP-derived net-sand/net-pay values do not reflect effective reservoir behavior and should be considered only as a crude approximation of reservoir performance;
- Naranja sands average 10.5 % porosities and 7 mD permeabilities: thus, they should be qualified as poor oil reservoirs; however, some of these thin sands are capable of production rates above 2000 BOPD; core-derived matrix permeabilities of about 10 mD are sharply contrasting with 10 Darcy average permeability derived from well interference tests. This implies the presence of a dual permeability system with the contribution of a fracture network.

Analysis of the NA-J4 reservoirs shows that fracture characteristics and influence on fluid flow are closely linked to lithofacies development. Where the NA-J4 consists of coastal plain facies, fractures are concentrated in the lower part of the reservoir, density is low, and only one set is developed. Where shoreface facies are dominant, fractures are distributed throughout the reservoir, and occur in two intersecting sets (Fig. 11). The variability in fracture density, spatial distribution and dip orientation in conjunction with the matrix properties combine to promote an increase of production rates from 800 BOPD to 10,000 BOPD.

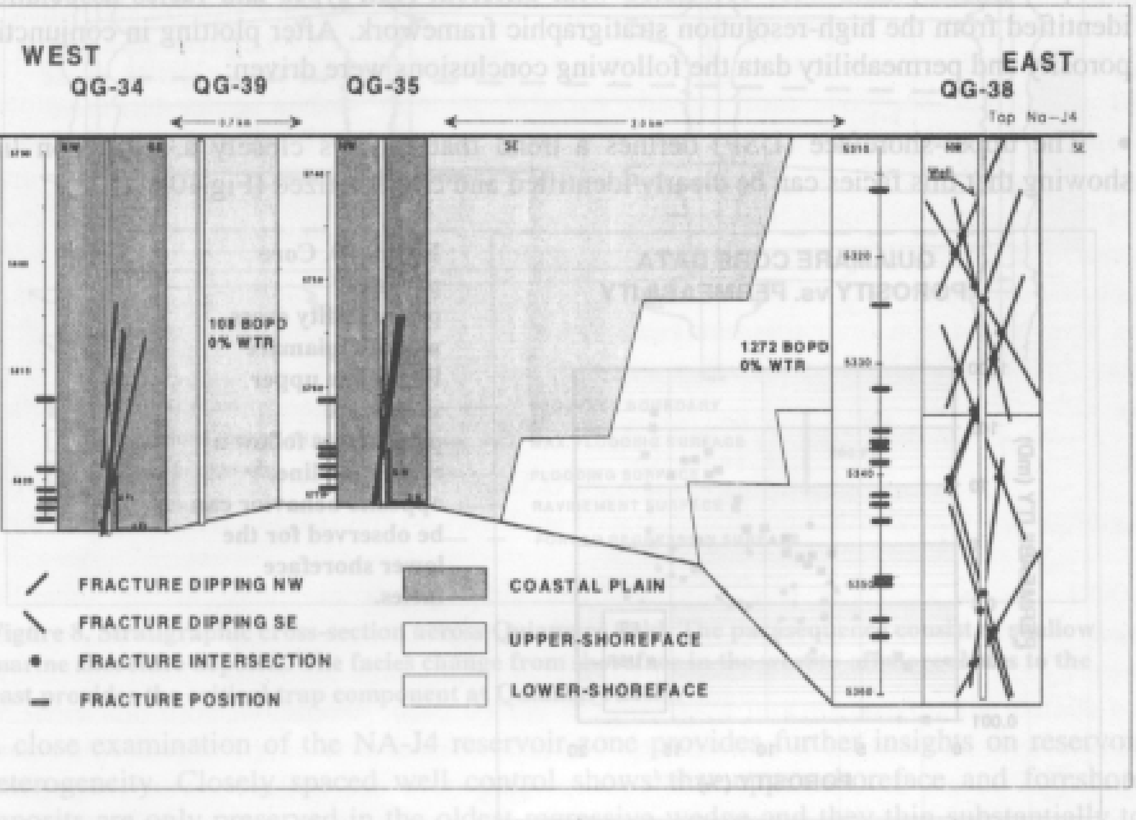

Figure 11. Stratigraphic cross section of NA-J4 reservoir showing the relation between natural fractures spatial distribution, and facies.

SEISMIC EXPRESSION:
Amplitude Anomalies and the Relationships Between Acoustic Impedance and Reservoir Quality.

The 2D seismic data across the Quiamare Field indicate zones of anomalously strong amplitude between the Oficina NA-G3 and VE-A3 horizons (Fig. 12).

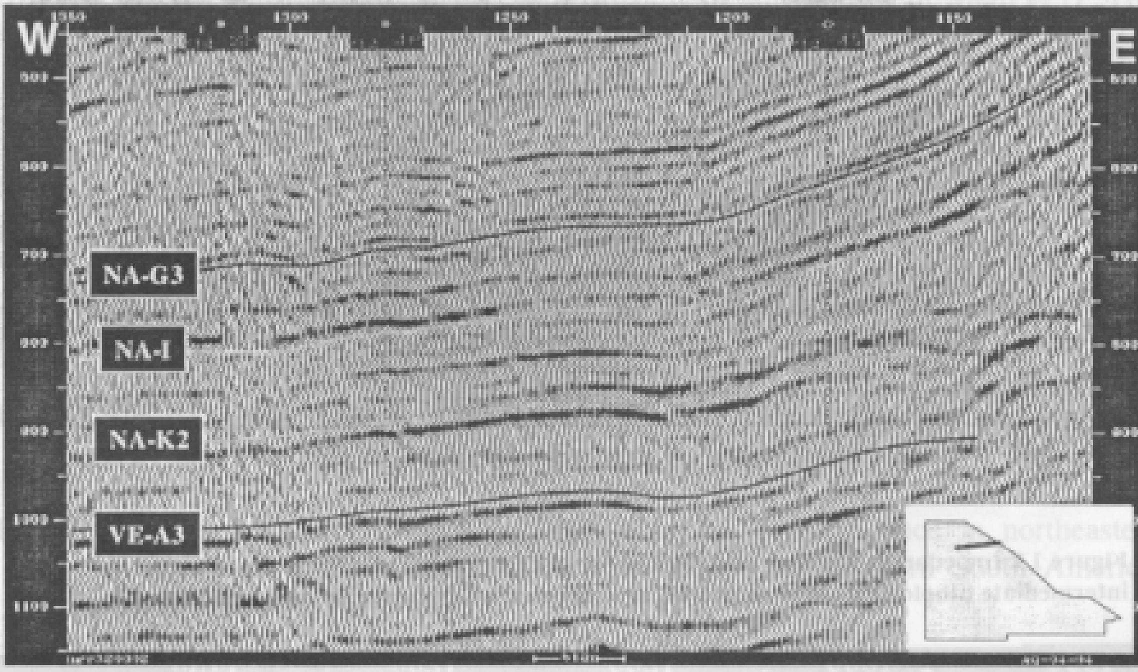

Figure 12. Seismic amplitude variations across Quiamare Field. Note in particular strong amplitudes at NA-K2 level, between wells OG48 and OG-47.

AVO work demonstrates that these amplitude variations are primarily a zero-offset effect. Modeling work suggests that any variations in fluid content within the reservoir sands would lead to amplitude variations of a smaller magnitude than those observed, due to the high acoustic impedance of the sediments in question. Neither can the anomalies be explained in terms of tuning effects.

Areal mapping of the anomalies shows a trend oblique to the structural axis and closely parallel to the observed depositional strike, supporting the inference that the anomalies are an expression of lithological variation, rather than a change in fluid content.

Petrophysical analysis of well log data, combined with the results of the sequence stratigraphic interpretation, enable a tentative association between relatively high acoustic impedance and lower shoreface poor-reservoir facies (Fig. 13). Inversion of the seismic data gives a representation in terms of acoustic impedance, in place of amplitude (Fig.14). Given an association between facies and impedance, facies variations (away from points of well control) may be directly interpreted from the inverted data, thereby providing valuable input into field development planning.

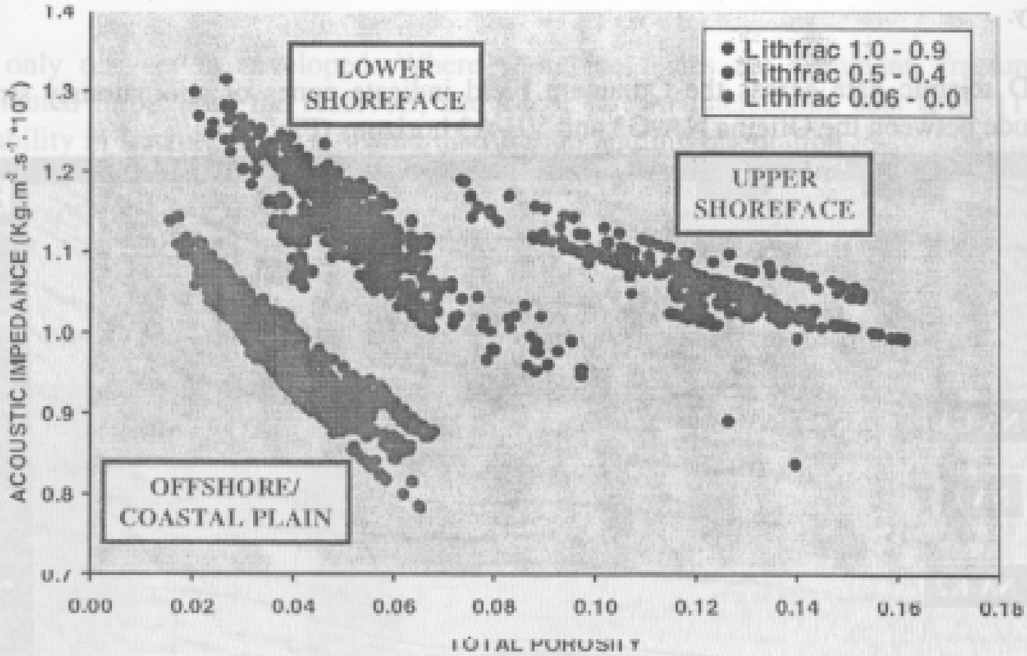

Figure 13. Impedance- porosity relationship for discrete ranges of gamma ray. Note how intermediate lithologies, lower shoreface, are represented by relatively high impedance

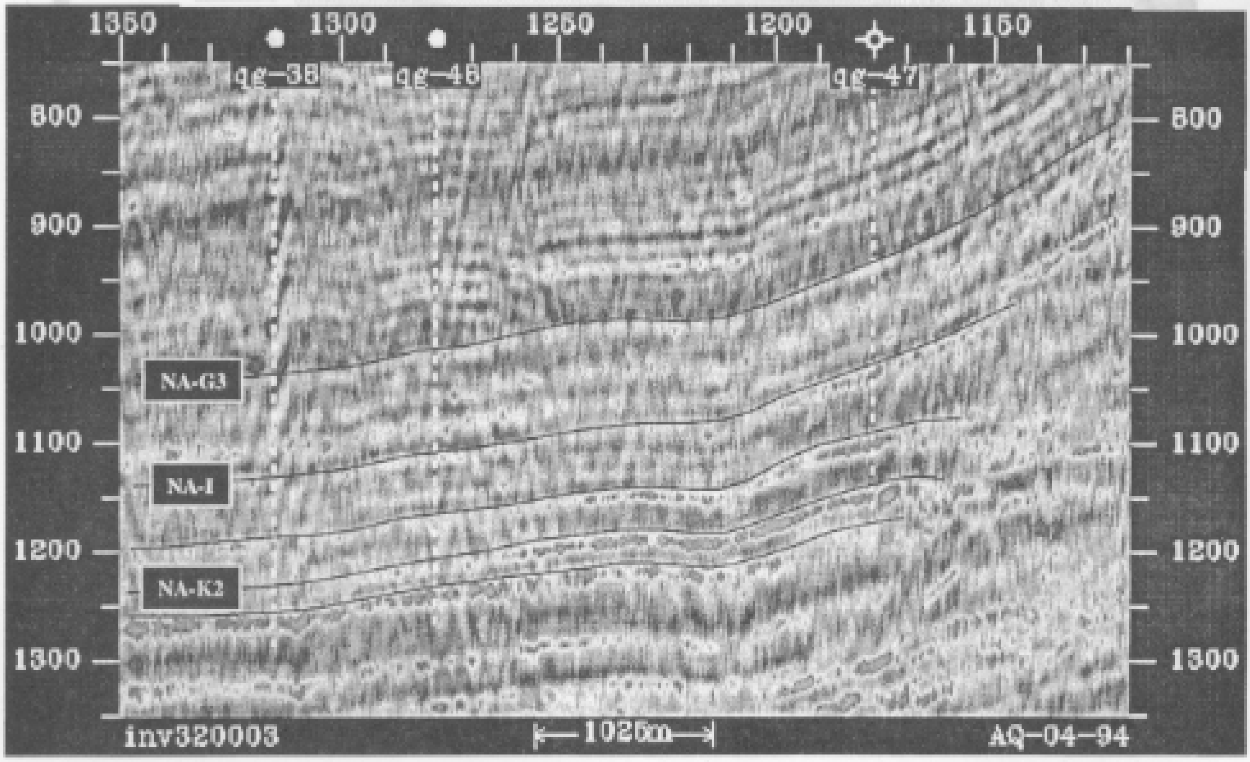

Figure 14. Inversion of seismic line shown in figure 10. Blue/ green = high impedance; yellow/ red = low impedance.

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