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APPLICATION OF GEOSCIENCE TECHNOLOGY IN A GEOLOGIC STUDY OF THE NATUNA GAS FIELD, NATUNA SEA, OFFSHORE INDONESIA

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ABSTRACT

The Natuna gas field is one of the world's largest natural gas accumulations with an estimated 222 TCF gas in-place (71% CO_2). The reservoir is a porous carbonate buildup within the Miocene Terumbu Formation covering approximately 310 km^2 with a maximum column height of 1638 m (crest at 2658 m subsea). The primary goal of the Natuna field geologic study was to provide a sound basis for construction of 3-D volumetric and production simulation models.

Five wells and 3500 line km of 2-D seismic form the primary data base for the geologic study of the Natuna reservoir. The framework for the project was a sequence stratigraphic analysis which defined 9 major time-stratigraphic units within the Terumbu carbonate at the field. Prediction of reservoir facies and quality away from well control required integration of a host of geologic and geophysical data. Seismic facies were mapped and calibrated at well control. Calibration involved tying the seismic facies to lithofacies derived from core description, thin-section petrography and petrophysical analysis of well logs. A strong link between depositional facies and porosity was established. Sequence-based depositional facies maps were constructed as guides for final porosity mapping. An independent geophysical analysis of reservoir porosity was also obtained using a velocity - porosity transform. Integrated porosity maps combined the geological and geophysical data using a contouring style drawn from company experience with Miocene and Holocene analogues. The porosity maps, together with data on permeability, saturation and net-to-gross were used to build the Natuna field volumetric and reservoir simulation models. Close linkages between the reservoir engineering and geoscience teams, together with strong central coordination by Esso Exploration and Production Natuna Incorporated (EEPNI), proved to be critical to project success.

INTRODUCTION

The Natuna concession lies approximately 225 km northeast of Natuna Island in the Indonesian territorial waters of the East Natuna Sea (Figure 1). The concession is retained under terms of a Production Sharing Contract between Pertamina and EEPNI. The block contains a large, isolated Miocene carbonate platform within the Terumbu formation known as the Natuna gas field. The as yet undeveloped field contains approximately 222 TCF total gas in-place (71% CO_2) within a stratigraphic closure with a basal area of 310 km^2. The field was discovered in 145 m of water by AGIP in 1973 (AL-1X). After securing the block in 1980, Esso acquired a 2-D seismic survey and drilled four delineation wells (L-2X, L-3X, L-4X and L-5X). With the exception of L-4X, each of the Esso wells penetrated the gas/water contact. The Esso seismic survey was reprocessed in 1990-1991 and together with the five wells provided the database for a 1991-1993 study involving geoscientists from Esso and Exxon Production Research (EPR) with guidance and support from Pertamina. The goals of the integrated study can be summarized as follows:

1. Evaluate the structural, stratigraphic, and diagenetic relationships within the Natuna field by integrating seismic, core, biostratigraphic, wireline well-log, and geochemical data.

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2. Build a sequence stratigraphic framework of the Natuna field to help delineate likely facies distributions and reservoir heterogeneities.

3. Understand the spatial and temporal development of porosity by re-examining the available core material.

4. Provide a detailed geologic model including structure, isopach, facies, and porosity maps for the purposes of reserve determination and input into reservoir simulation models.

This paper describes the methods used to develop an integrated geologic model for the Natuna field (Figure 2). Previous Exxon publications on Natuna include: Sangree (1981), Eyles and May (1982), May and Eyles (1985), and Rudolph and Lehmann (1988).

Regional Setting and Geologic History

The East Natuna-Sarawak Basin consists of a broad, crescent-shaped basin located off the northwest coast of Borneo (Figure 1). The basin is bounded on the west by the north-south trending Natuna Arch. The Terumbu shelf sits at the eastern edge of the arch and consists of a north - south trending high which has been fragmented by Tertiary extensional tectonics into a mosaic of normal fault blocks. Faulted highs were the preferential sites for carbonate growth during the middle to late Miocene and the early Pliocene. Basement in the area consists of Cretaceous granitic and meta-volcanic rocks.

Strata of the East Natuna-Sarawak Basin record a complex geologic history that includes rifting and sea floor spreading focused to the north in the South China Sea, as well as convergence and subduction along the northwest coast of Borneo (Hamilton, 1979). Although initial rifting of the proto-China margin may have commenced as early as latest Cretaceous or Paleocene, sea-floor spreading in the South China Sea Basin did not occur until Oligocene through Miocene time (Taylor and Hayes, 1983). During rifting and subsequent sea-floor spreading, the Borneo continental margin underwent considerable stretching and differential subsidence (Hamilton, 1979; Taylor and Hayes, 1983). This extensional deformation produced a broad complex of structural blocks, upon which carbonate buildups nucleated during the middle Miocene. In the case of the Natuna field, carbonate

growth terminated with the end of the Miocene in conjunction with a phase of rapid subsidence associated with loading by an orogenic front and accretionary prism in northwestern Borneo (Hamilton, 1979).

The stratigraphy and burial history of the East Natuna Basin combined to create a rich hydrocarbon province (Figures 3 and 4). Mature source facies are provided by the Gabus and Arang formations which contain basal coal-bearing fluvial and coastal plain deposits and gradually increase upward in marine components. The platformal carbonates of the Terumbu Limestone form the reservoir of the Natuna field. Terumbu carbonate growth was localized on faulted Arang highs associated with the rifting of the South China Sea. In the Terumbu shelf area, the Terumbu ranges from 780 to 2900 m in thickness. Porosity averages 14.5% in the five Natuna field wells. Solution-enhanced secondary porosity plays a major role particularly in the upper part of the Terumbu. Carbon isotopic evidence indicates that the elevated carbon dioxide content of the Natuna field resulted from the thermal breakdown of deeply buried carbonates. Temperatures at the field are too low for carbonate breakdown to be occurring locally. Deeply buried and as yet unidentified Terumbu carbonate bodies to the southeast of the field are the most likely source of the carbon dioxide. Basinal facies consisting of non-porous carbonates and shales form the lower lateral seals for the Natuna accumulation. Top seal and upper lateral seal for the upper Terumbu is provided by the Muda formation (Pliocene to Recent). The basal Muda is characterized by thick, deep-water shales which grade upwards into intercalated shales, siltstones and sandstones.

METHODS

Core Description, Petrographic Analysis and Biostratigraphy

Descriptions of the 295 meters of Natuna field core emphasized identification of dominant grain and pore types, lithofacies, diagenetic features, parasequences, and sequence boundaries. Whole core analysis was supplemented by studies of 570 sidewall cores. Petrographic analysis was carried out using polished thin-sections which had been impregnated with blue epoxy to highlight open pores and stained with Alizarin Red S to aid in the differentiation of

dolomite and calcite. Particular emphasis was placed on identification of porosity types using the nomenclature of Choquette and Pray (1970).

Biostratigraphic age control was provided by EPR and Robertson Research studies which included wells from the field as well as from outside of the Natuna field concession. As age indicative fauna are scarce within the Terumbu carbonates themselves, much of the intra-Terumbu age definition relies on seismic ties to age equivalent basinal strata containing abundant age diagnostic micro and nanno-fossils.

Well Log Analysis

Petrophysical analysis of the Natuna field was complicated by high gas saturations and elevated temperatures. A proprietary, work station-based software package (SOLAR) was used to construct and interpret a quality controlled database of log, core and well test information (Figure 5). Accurate interpretation of reservoir porosity involved making environmental corrections to numerous log measurements. The neutron tool was particularly vulnerable to the hostile reservoir conditions. Figure 6 depicts a suite of curves from raw neutron porosity (track 3) to fully corrected neutron curves (tracks 4 and 5) from an interval of the L-3X well. Downhole temperatures nearing 300 °F and gas saturations in excess of 90% (track 1), result in raw data that is not representative of true reservoir porosity. However, using the LASER temperature and gas correction algorithm within SOLAR a close match between neutron and density porosities is achieved and the fully corrected neutron curve is found to closely track porosity data obtained from core (track 5).

Seismic Interpretation and Sequence Stratigraphy

Approximately 3,500 line kilometers of seismic data were interpreted using a work station-based interactive interpretation package. Sequence boundaries were picked on the basis of reflection geometries such as toplap, top truncation and onlap (Mitchum et al. 1977). Wells were tied to the seismic by convolving a 20-Hz minimum phase pulse with a check shot corrected impedance series derived from environmentally corrected, blocked sonic and density logs. Sequence boundary picks were refined through analysis of the vertical stacking patterns seen in the well logs and in core. Work station software enabled interpretation on seismic cross sections, flattened to a particular horizon, enabling interpretation of restored sections to reduce the effects of post-depositional fault offsets and/or rotation. Despite the many virtues of the interactive work station, it was found that interpretation of subtle stratigraphic geometries was best handled with large-scale plots and "old-fashioned" color pencils. A total of 9 regionally extensive sequence boundaries were defined within the Terumbu of the Natuna field (Figures 4 and 7).

Seismic Velocity Analysis

Figure 8 shows transit time versus log-derived porosity for Terumbu carbonates. This is the fundamental relationship that makes it possible to estimate carbonate porosity from seismic velocity. Sequence-keyed transit times were derived from well check shot data. Log porosities are averages over the check shot intervals. This relationship permits predictions to ± 4% porosity provided that the analysis is made within a pure carbonate section. Contamination of the section by low velocity shales could result in erroneously high apparent carbonate porosities. Fortunately, where it has been penetrated in the Natuna field, the Terumbu is nearly a pure carbonate with the exception of the uppermost sequences at the L-5X well (Figure 7). Mapping of seismic velocity derived porosity was performed at a 1:50,000 scale using velocity functions spaced 500 m apart along each seismic line.

Seismic Facies and Depositional Facies Analysis

Seismic facies maps were constructed for each sequence using internal reflection geometries and their relationship to the confining sequence boundaries. Additional seismic attributes such as amplitude and continuity were also identified. Based on the procedure outlined by Mitchum et. al. (1977) and Ramsayer (1979) for seismic facies analysis, eight main seismic facies were identified (Figure 9).

Depositional facies were identified by their seismic facies character and by their lithofacies as calibrated from core and well log analysis. Depositional facies maps were used in conjunction with well data and seismic velocity-derived porosity estimates to guide contouring of the final, integrated porosity maps (Figure 2).

Structure, Isopach and Porosity Mapping

Time and depth structure and isopach maps were created for each Terumbu sequence. Sequence-averaged porosity maps were generated using well data, seismic velocity derived porosity maps and depositional facies maps. Integration of these data required hand contouring of each sequence with frequent comparisons made to other Miocene carbonate reservoirs as well as modern analogues.

Porosity - Permeability Relationships

Maps of sequence averaged permeability were an essential input into the reservoir simulation model. The distribution of permeabilties was estimated using a porosity permeability transform based on a calibration to Terumbu core and well tests performed in the five Natuna field wells (see Fenter and Hadiatno, this volume). A strong correlation between lithofacies and porosity and permeability lends increased confidence to this method of permeability estimation (Figure 10).

Multi-Disciplinary Integration

EEPNI coordinated the efforts of the various technical teams. Integration involved not only the specialties listed above, but also geochemistry, burial history analysis, source rock mapping, seismic reprocessing and reservoir engineering. For example, the log analysis and seismic interpretation teams worked closely together in an iterative fashion using synthetic seismograms and well log stacking pattern analysis to refine the sequence stratigraphic framework and reservoir zonation. In a like manner, the sequence stratigraphic framework provided the context for geochemical analyses of Terumbu limestones and dolomites.

RESULTS

Terumbu Petrography

Lithofacies within the Natuna field are characterized by distinct depositional textures, diagenetic features, porosities and permeabilities. Five distinct lithofacies are represented in the 295 meters of core material from the Natuna field (Table 1). Although some of these facies can also be recognized in descriptions of sidewall cores from the L-3X and L-4X wells, whole

core is required to confidently assign lithofacies, particularly when distinguishing between boundstones and grainstones. They are defined by their most abundant skeletal grains and their texture or mud content, following the classification of Dunham (1962). In decreasing order of reservoir quality the five main lithofacies are: (1) Coral-Red Algal Boundstones/Grainstones, (2) Coral-Red Algal, Echinoderm Grainstones, (3) Red-Algal, Echinoderm-Mollusk Packstones, (4) Red-Algal, Benthic Foraminifera Packstones, and (5) Planktonic Foram Wackestones/Mudstone. Identification of lithofacies was particularly important in view of their control on porosity and permeability (Figure 10). The influence of original depositional fabric was unexpected given that secondary, dissolution enhanced porosity was a major pore-type in most lithofacies (Table 1). One explanation for this relationship is the greater abundance of aragonitic corals in Lithofacies 1 and 2 which contribute to their higher porosities, as these grains are preferentially leached due to their greater solubility.

Well Log Analysis

Analysis and interpretation of the Natuna log data was calibrated to core measurements and performed within a sequence stratigraphic framework. Figure 7 shows a well log cross section from north to south through the field. Gamma ray curves (left-hand track) show a clean carbonate buildup with only the uppermost portions of L-5X and L-3X encountering significant shale. Porosity (right-hand track) averages 14.5% for all of the wells with the upper Terumbu having the highest values. Lower Terumbu sequences have lower average porosities due to compaction and cementation. Only the L-2X well, located at the southwest periphery of the field shows a significant section of lower porosity Terumbu. No significant barriers to gas flow were encountered that might segment the field into smaller compartments.

Seismic Interpretation and Sequence Stratigraphy

Figure 11 shows a north - south seismic section through the Natuna field. The progressive reduction in areal extent (retrogradation) of the platform can be clearly seen with the uppermost Miocene Terumbu sequences being characterized by pinnacle reef development. Also note the underlying structural control on carbonate platform development. Many of

the faults which set up the preferred sites for platform nucleation remained active during lower Terumbu deposition giving rise to individual fault blocks with variable Terumbu thicknesses. Although they are not shown in Figure 11, systems tracts were interpreted within the thicker sequences. Systems tracts were found to exert a significant control on reservoir development with highstand tracts being most porous. The following observations were found to hold true for most systems tracts:

1. Highstand systems tracts are thickest over the crest and at the edges of the central part of the platform (main bank area, Figure 11). In deeper-water positions highstand carbonates are thin.

2. Lowstand systems tracts are restricted to topographic lows, occurring most commonly in positions where they onlap the platform slope. They have not been sampled by drilling.

3. Transgressive systems tracts are widespread, but thin. They are only resolvable by gamma-ray pattern recognition over the highest parts of the platform. They thicken off-platform where they are locally resolvable on seismic sections.

Seismic and Depositional Facies and Porosity Mapping

A seismic facies map and time equivalent depositional facies and porosity maps for the Ultramarine sequence are shown in Figure 12. This sequence shows the most widespread occurrence of mounded seismic facies. These mounds are interpreted as forming fringing reef complexes.

High-amplitude parallel seismic facies occur in protected areas inboard of the fringing mounds on the western side of the platform. This facies is interpreted to have been deposited in a low to moderate energy setting. Parallel and thin seismic facies also occur on the bank tops and may represent low-energy lagoonal sediments. Low-amplitude, progradational sigmoidal to oblique seismic facies fringe the platform on all sides. This facies is interpreted to have been deposited under moderate energy conditions.

The contouring style of the porosity map clearly reflects the interpreted control of depositional facies on reservoir porosity. Note that the mounded facies

(fringing reef complex) in the northwest is separated from the main bank by a trough containing lower porosity carbonate (Figure 12). This interpretation is also supported by seismic velocity derived porosity analysis. The northwestern banks are a possible target for a separate development if they can not be efficiently drained from production wells positioned over the platform crest.

CONCLUSIONS

This stratigraphic and structural study was based on an integrated data set comprising seismic, core descriptions, core analysis, wireline well logs, biostratigraphic information, and geochemical data. We recognized 9 depositional sequences ranging in age from early Miocene to early Pliocene (16.5 Ma - 5.2 Ma). Seismic facies, depositional facies and porosity maps were generated for each Terumbu sequence to show the gross distribution of porous facies. In addition, sequence-keyed structure and isopach maps were constructed to aid in volumetric calculations. A review of the volumetric analysis of the Natuna field can be found in Fenter and Hadiatno (this volume). Based on the results of this study, we offer the following general conclusions for the Natuna field:

1. The Natuna field is a large structurally controlled carbonate platform which reached its greatest extent in the middle Miocene before undergoing retrogradation associated with increased subsidence during the late Miocene.

2. The field and the surrounding area were tectonically active throughout Terumbu deposition, although most faults terminate within the lower Terumbu.

3. At the Natuna field, the Terumbu Formation is a clean, porous carbonate for almost its entire 1600+ meter thickness. No shale breaks have been penetrated within the reservoir, but nonporous facies occur as basinal equivalents to the platformal facies (lateral seals).

4. Terumbu porosity and permeability decreases with depth due to physical compaction, pressure solution and associated cementation.

5. Diagenetic alteration of rock fabrics is

widespread, with leaching and moldic porosity development attributed to freshwater phreatic diagenesis.

6. Porosity and permeability show a strong relationship to lithofacies, and depositional texture is the primary control on reservoir porosity and permeability.

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TABLE 1

CHARACTERISTICS OF THE MAJOR LITHOFACIES OBSERVED IN THE TERUMBU LIMESTONE CORES FROM THE NATUNA FIELD

| LITHOFACIES	1	2	3	4	5
DEPOSITIONAL TEXTURE	CORAL-RED ALGAL BOUNDSTONES & GRAINSTONES	CORAL-RED ALGAL-ECHINODERM GRAINSTONES	RED-ALGAL, ECHINODERM-MOLLUSC PACKSTONES	RED-ALGAL, BENTHIC FORAMINIFERA PACKSTONES	PLANKTONIC FORAMINIFERA WACKESTONES & MUDSTONES
MAJOR GRAIN TYPES	CORAL, RED ALGAE	CORAL, RED ALGAE	RED-ALGAL, SKELETAL TYPES	BENTHIC FORAMINIFERA, RED-ALGAE	PLANKTONIC FORAMINIFERA
MINOR GRAIN TYPES	ENCRUSTING RED ALGAE AND FORAMS ECHINODERMS BENTHIC FORAMS	ECHINODERMS BENTHIC FORAMS DIVERSE ABRADED SKELETAL DEBRIS	ECHINODERMS BENTHIC AND ENCRUSTING FORAMS BIVALVES BRACHIOPODS BRYOZOANS	CORAL DEBRIS MOLLUSCS BRYOZOANS	OSTRACODS SPONGE SPICULES QUARTZ SILT CLAYS
SEDIMENTARY STRUCTURES	BORINGS BURROWS	BURROWS	BURROWS	BURROWS	BURROWS, ARGILLACEOUS SEAMS
MAJOR PORE TYPE	MOLDIC	MOLDIC	MOLDIC	MOLDIC	INTRAPARTICLE
MINOR PORE TYPE	INTERPARTICLE INTRAPARTICLE	INTERPARTICLE INTRAPARTICLE	INTER-CRYSTALLINE	INTERPARTICLE	MOLDIC
AVG. POROSITY ± STANDARD DEV.	25% ± 3.2 n = 123	20% ± 6.6 n = 190	14% ± 5.0 n = 267	9% ± 3.5 n = 53	3% ± 1.9 n = 98
AVG. PERM. ± STANDARD DEV.	73 ± 168 md	22 ± 29 md	11 ± 32.2 md	0.2 ± 0.23 md	0.2 ± 1 md
MEDIAN POROSITY/ PERMEABILITY	26% / 41 md	22% / 17 md	13% / 1.6 md	9% / 0.2 md	3% / 0.1 md
DIAGENETIC MODIFICATION	DISSOLUTION MICRITIZATION MINOR CALCITE CEMENTATION	DISSOLUTION MICRITIZATION MINOR CALCITE CEMENTATION	CALCITE CEMENTATION, DOLOMITIZATION FRACTURING	DISSOLUTION MICRITIZATION CALCITE CEMENTATION	COMPACTION CEMENTATION PRESSURE SOLUTION
ENVIRONMENT	REEF	PLATFORM MARGIN REEF FLAT	OPEN PLATFORM, PLATFORM INTERIOR	PLATFORM INTERIOR-MARGIN TRANSITION	SLOPE TO BASINAL
CORED WELL PENETRATIONS	L-3X, AL-1X	L-2X, L-3X, AL-1X	L-2X, AL-1X	L-3X	L-2X
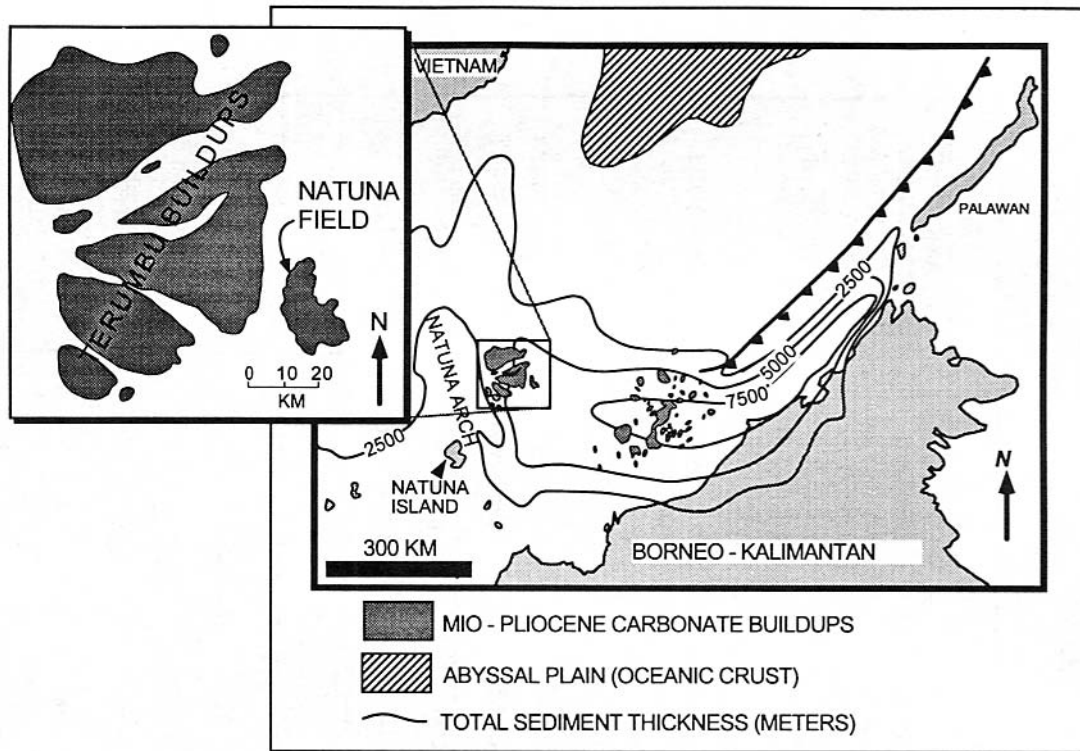
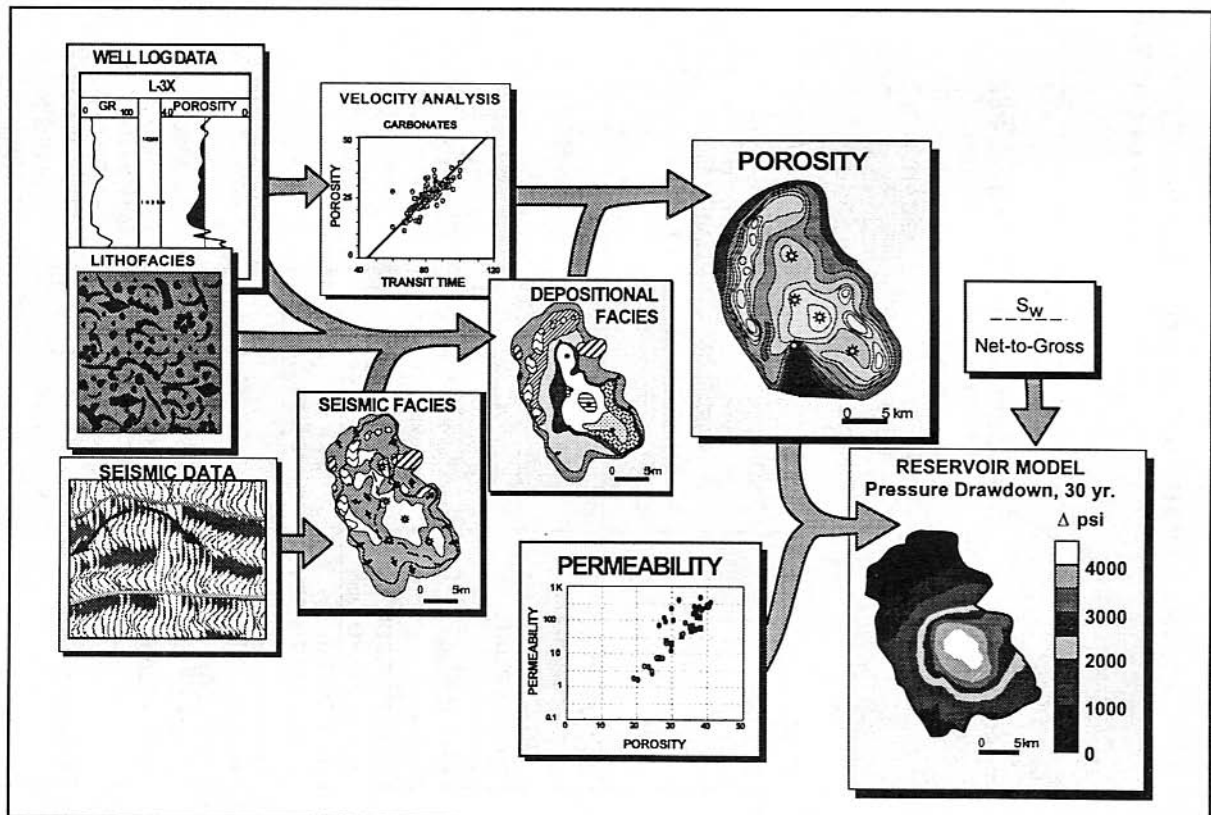**FIGURE 1** - Natuna Field Location Map
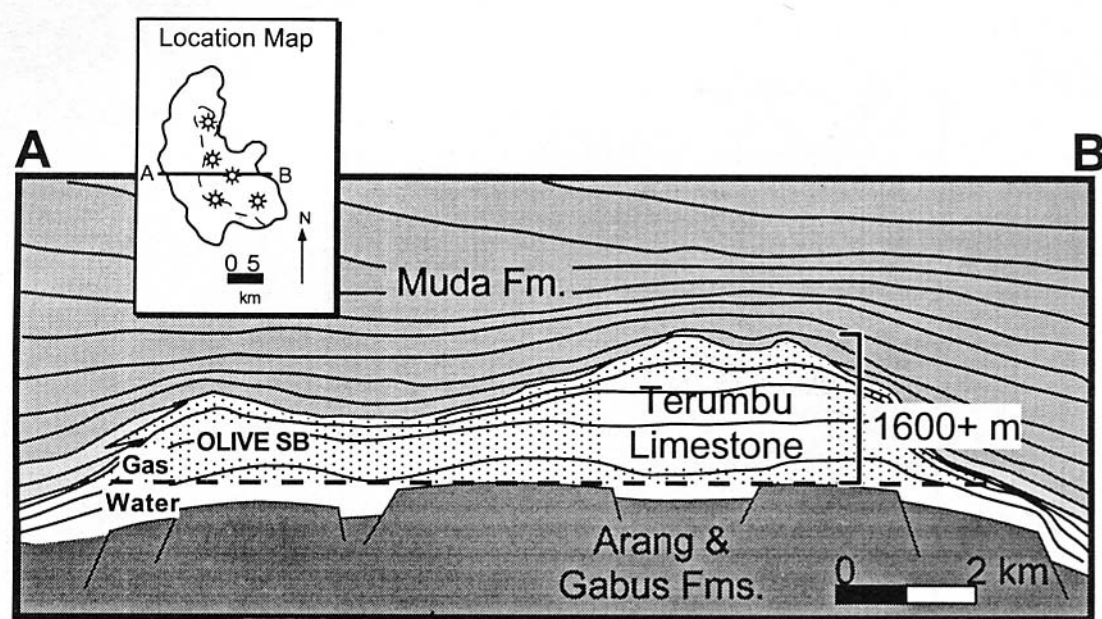

FIGURE 2 - Natuna Geoscience Technology Flow Chart.

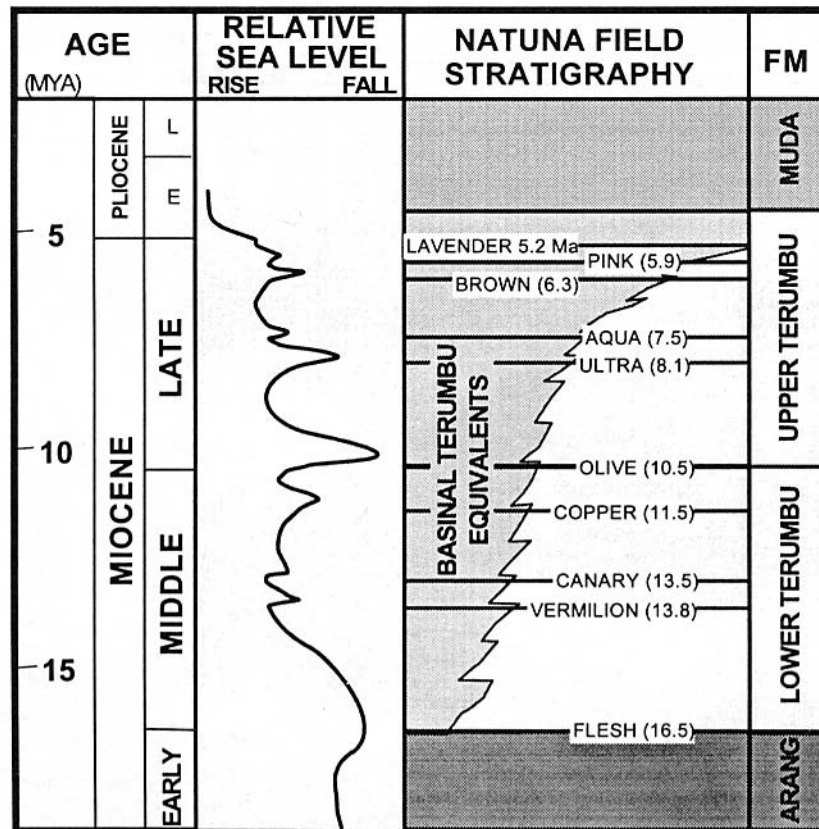**FIGURE 3** - Natuna Gas Field-Schematic Cross Section.

FIGURE 4 - Natuna Gas Field-Chronostratigraphy.

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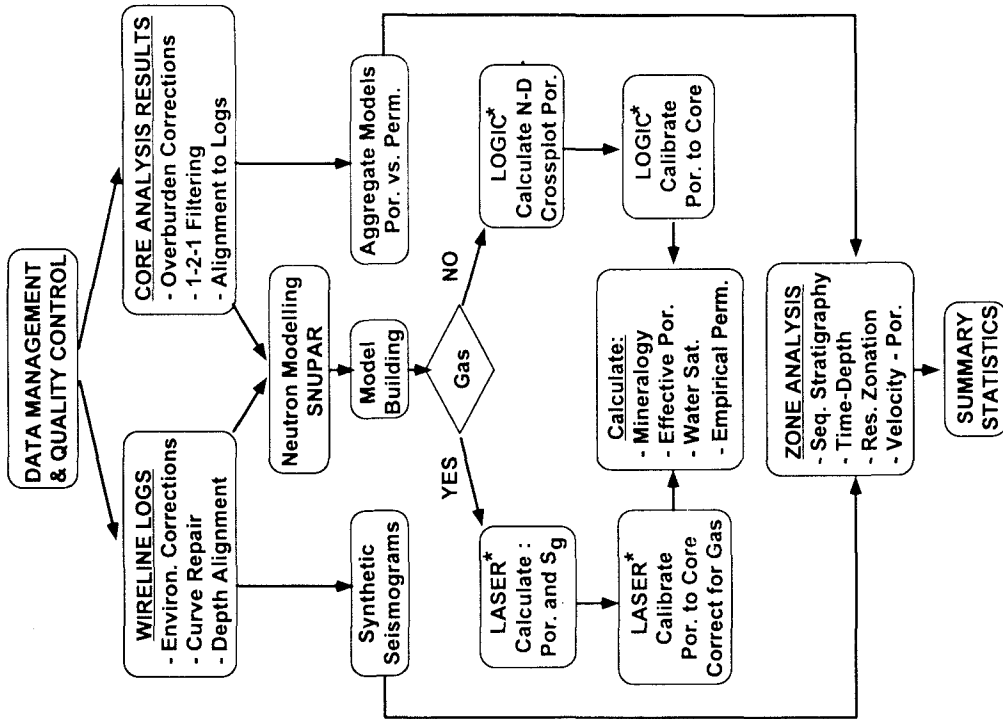**FIGURE 6** - Well Log Analysis- Environmental Correction and Core Calibration.

FIGURE 5 - Flowchart of Petrophysical Procedures.
* = Modules within SOLAR,
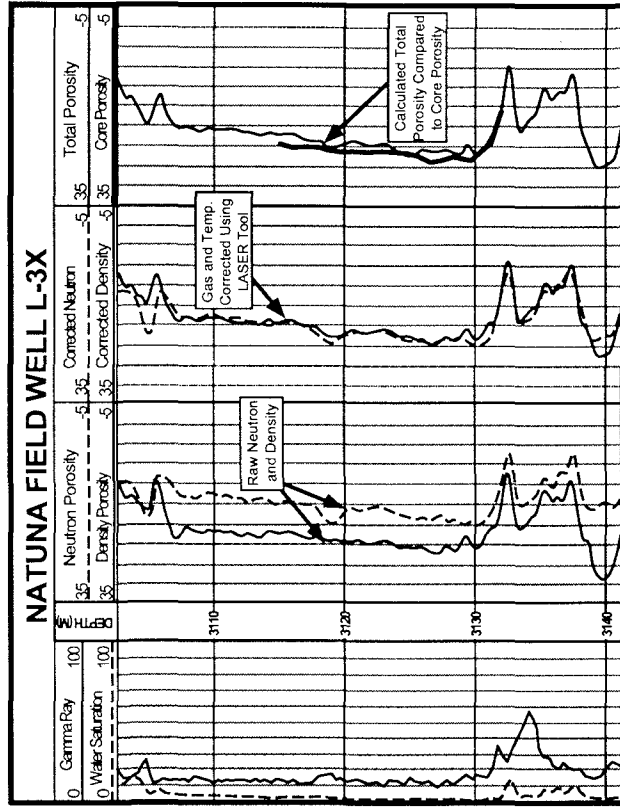a Proprietary Petrophysical
Analysis Computer Application.
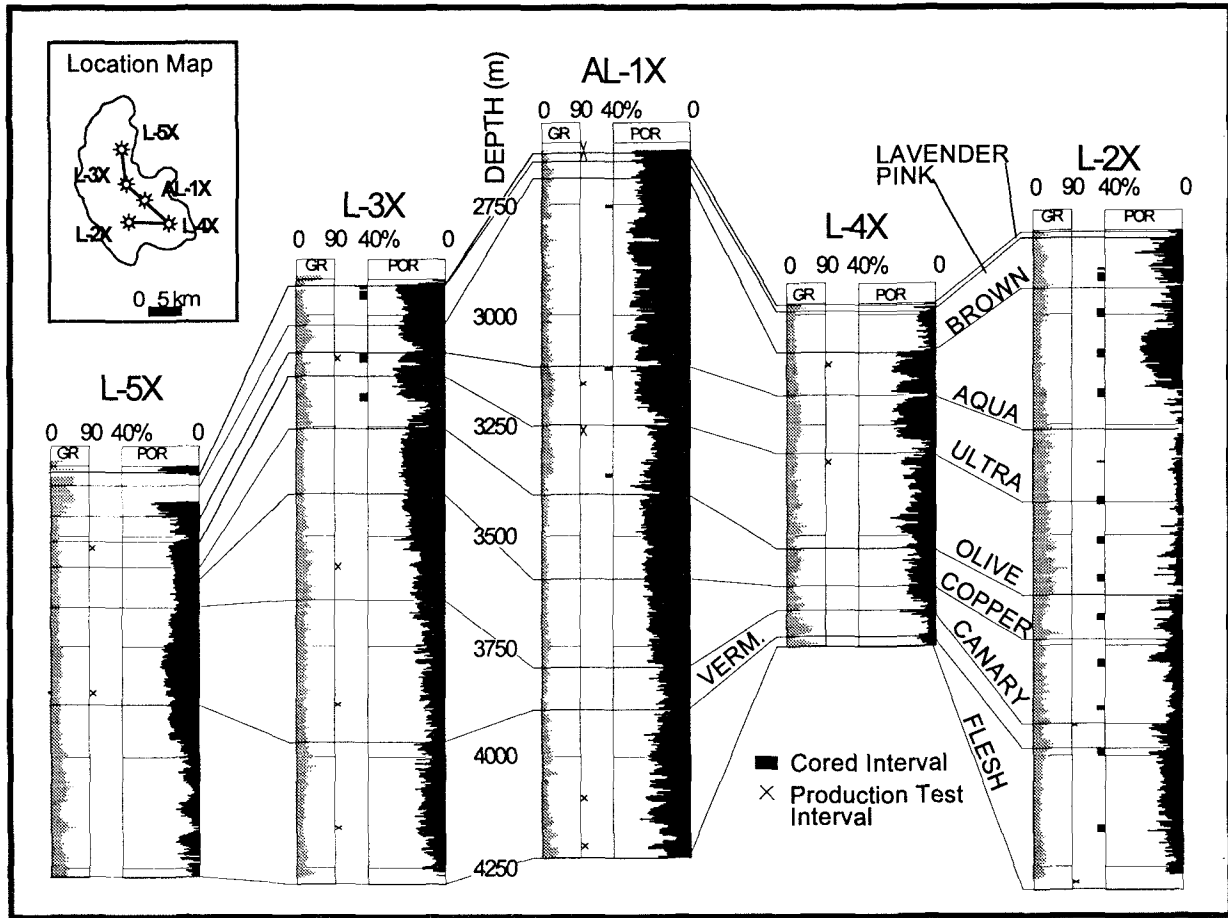
FIGURE 7 - Well Log Cross Section through Natuna Field.
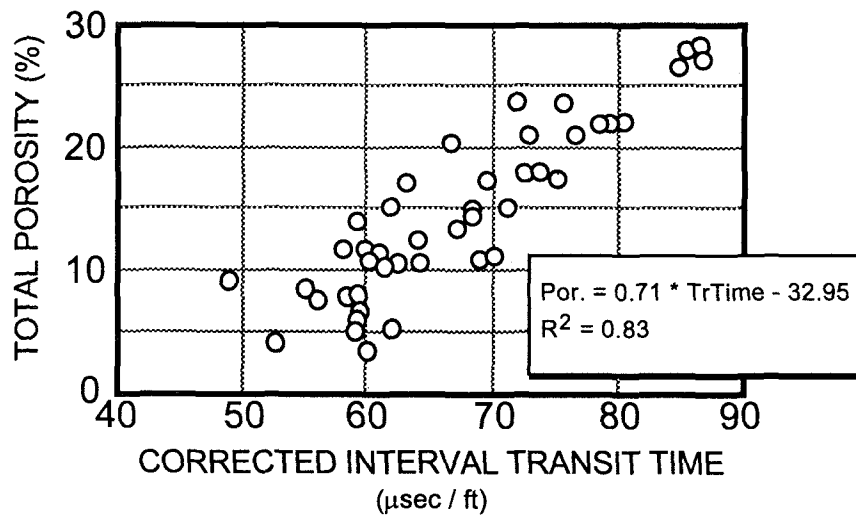(Ages of Sequence Boundaries shown in Figure 4)

FIGURE 8 - Total Porosity (from Logs, Averages for Check Shot
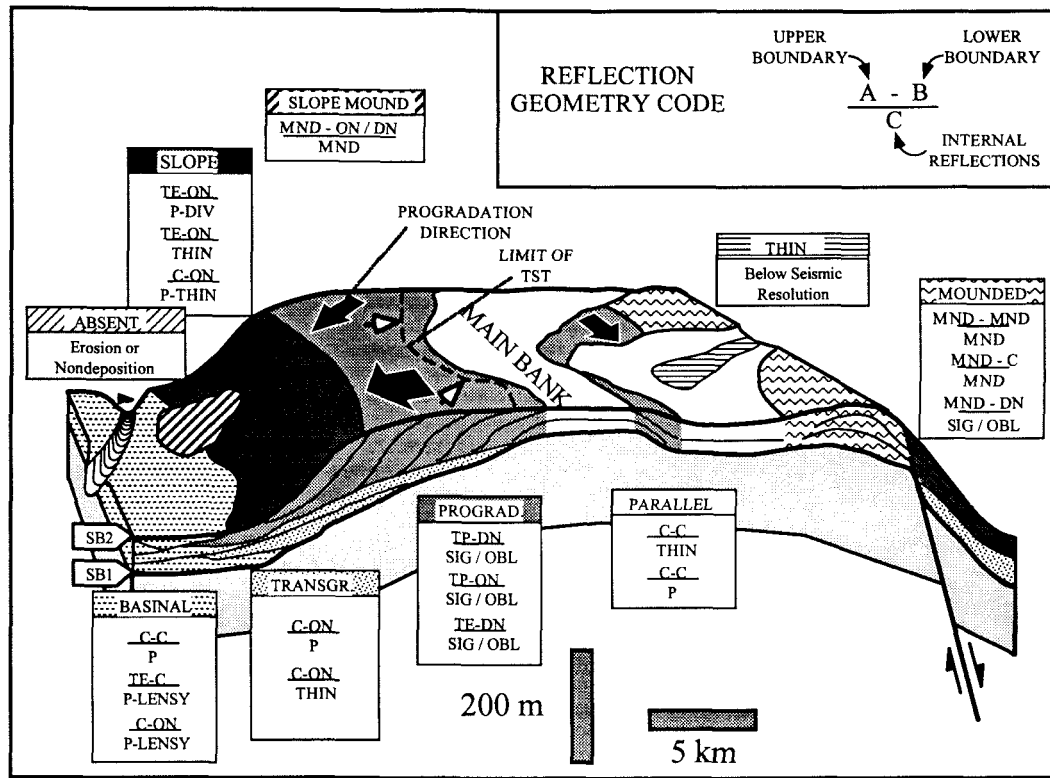Intervals) versus Check Shot Corrected Interval Transit
Time.

FIGURE 9 - Natuna Field Seismic Facies Key. C = Concordant, MND = Mounded,
P = Parallel, TP = TopLap, ON = Onlap, DN = Downlap,
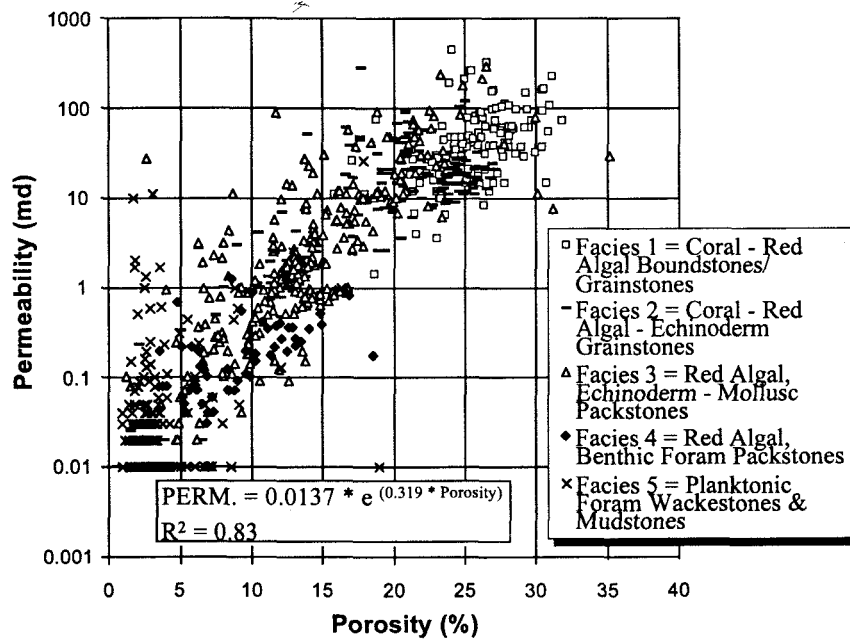TE = Truncation/Erosion, OBL = Oblique, SIG = Sigmoidal

FIGURE 10 - Natuna Field Porosity vs. Permeability by
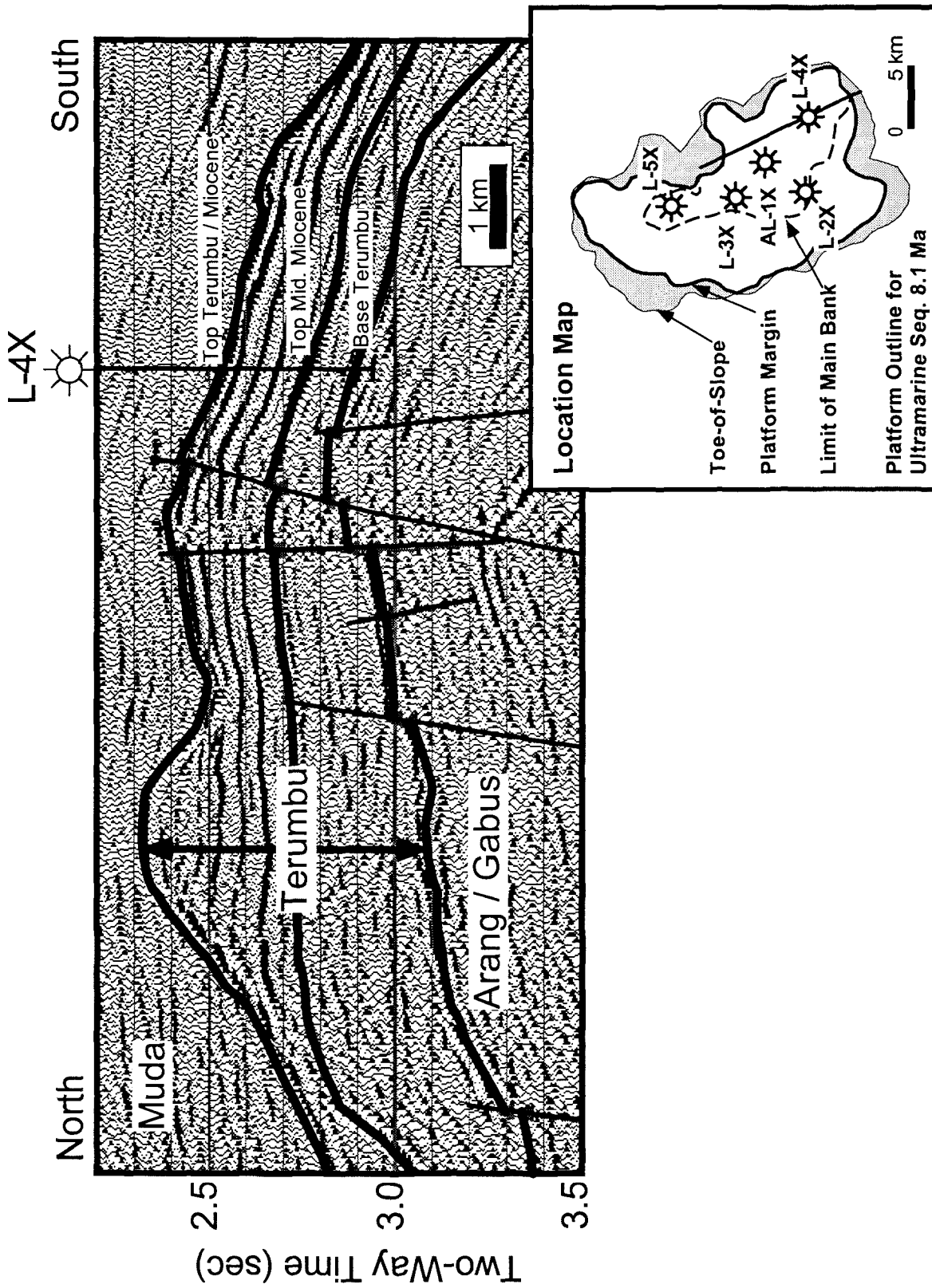Lithofacies (Data from Core)

FIGURE 11 - Seismic Section Through Natuna Field (Gas - Water Contact at Approx. 3 Sec). Note retrogradation of platform in Upper Miocene Section where high-amplitude reflections mark Enhanced transgressive systems tracts intercalated with more porous highstands.
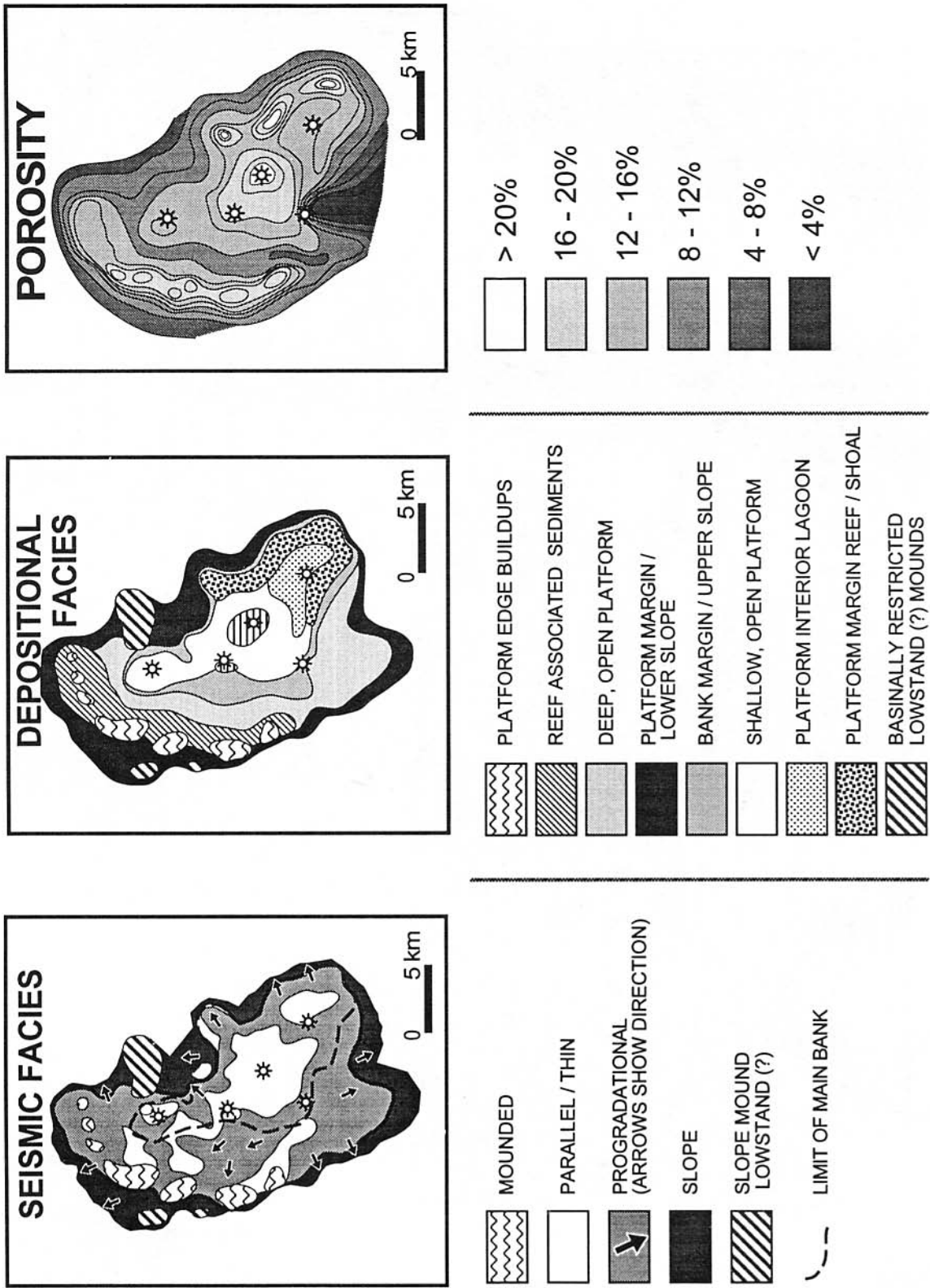
POROSITY

- > 20%
- 16 - 20%
- 12 - 16%
- 8 - 12%
- 4 - 8%
- < 4%

DEPOSITIONAL FACIES

- PLATFORM EDGE BUILDUPS
- REEF ASSOCIATED SEDIMENTS
- DEEP, OPEN PLATFORM
- PLATFORM MARGIN / LOWER SLOPE
- BANK MARGIN / UPPER SLOPE
- SHALLOW, OPEN PLATFORM
- PLATFORM INTERIOR LAGOON
- PLATFORM MARGIN REEF / SHOAL
- BASINALLY RESTRICTED LOWSTAND (?) MOUNDS

SEISMIC FACIES

- MOUNDED
- PARALLEL / THIN
- PROGRADATIONAL (ARROWS SHOW DIRECTION)
- SLOPE
- SLOPE MOUND LOWSTAND (?)
- LIMIT OF MAIN BANK

0   5 km

FIGURE 12 - Representative Maps for the Ultramarine Sequence (8.1 Ma)