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Petroleum Engineering Studies Educational Model

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ABSTRACT

PRESEM is a computer aided field development training system used in the Petroleum Engineering postgraduate and final year undergraduate courses at Imperial College.

PRESEM provides an integration of many of the activities which go into field development from drilling to the design of surface facilities, economic forecasting of pre performance and application to regulatory authorities.

The core of the PRESEM system consists of a data base which is generated by the system supervisor through a menu driven suite of programs simulating the properties of a given or hypothetical oil field. The data base contains the geological description of the reservoir, rock and fluid properties, presented as mud and electrical logs, RFT and production test data, core and PVT analyses. These vary in accordance with the depth and location of the exploration wells chosen by the user with reference to the formation top surface map.

PRESEM also contains many auxiliary programs including Schlumberger type log plotting, log-interpretation, pressure analysis, phase package for separator design, reserves estimates by Monte-Carlo analysis and economic feasibility analysis.

The paper describes the basic features of PRESEM and presents a case study.

INTRODUCTION

Computer aided teaching systems have been used in the Petroleum Engineering MSc and undergraduate courses at Imperial College since 1977[1] [2][3]. The MSc is a one year

References and illustrations at end of paper.

'conversion' course which the PRESEM project plays an important part, allowing students to apply knowledge gained in a wide range of theoretical courses. PRESEM simulates a field exploration and development project in which students are assigned roles as members of an operating company. The operating company sets out to explore a licenced block in UKCS (United Kingdom Continental Shelf) and reservoir properties represent those of typical North Sea oil fields. However, the system is entirely flexible and contains a menu driven Set Up module which allows the 'supervisor' to set up the properties of many different types of fields. PRESEM consists of three principal modules.

The Set Up Module, used by the supervisor, rests on a number of equations which are used to generate fieldwide variations in reservoir geometry, geology and petrophysics. The equations are given sufficient flexibility to match a range of reservoir characteristics.

The Exploration Simulation Module allows each operating company to 'drill' a number of wells into the reservoir model. The maximum number of wells which can be drilled is limited at the discretion of the supervisor from the Set Up Module. PRESEM now presents the students with a mudlog, cores, electrical well logs, production tests and PVT data specific to the coordinates of the field in which the well is drilled.

The Tools Module consists of a range of special applications software, such as those for pressure analysis, log interpretation, regression based EOS, etc. These, along with other computer systems and analytical techniques, taught in the lecture courses, allow the operating company to analyse the well test data to evaluate potential recoverable hydrocarbon reserves, and hence, to set out and to make an economic assessment of the development plan. At Imperial College the project culminates with a public hearing in which each operating company, typically consisting of five students presents their case and is questioned by representatives from industry.

SET UP MODULE

Set Up allows the supervisor to define the reservoir geometry, geology and rock and fluid properties as shown in Figure-1. Set Up consists of the following sub-modules:

[A] Reservoir Geometry: This is where the Unconformity Surface Map, Reservoir Layers and Faults are defined. The stratigraphy is represented by a series of quadratic equations of the form:-

$$z = z_{\text{disp}} [A(x+dx)^3 + B(x+dx)^2 + C(x+dx) + D + E(y+dy)^3 + F(y+dy)^2 + G(y+dy) + H(x+dx)(y+dy)] \quad (1)$$

where z_{disp} , A, B, C, D, E, F, G and H are the constants of the quadratic equation; x, y and z represent the lateral and vertical coordinates, and dx and dy represent the shift of the surface from a given reference point.

Contouring and mapping utilities are available in the Set Up Module for graphical representation of the top view or the stratigraphy at any desired cross section.

Faults are assumed to be planal and defined by a series of equations of the following form:-

$$A(x+dx) + B(y+dy) + C = Z \quad (2)$$

where the constants A and B are given by the user. The shift parameters dx, dy and constant c are entered as constants but they vary depending on the position of the last fault position with regard to previously defined faults which will obviously not only displace the strata but pre-existing faults as well, thereby changing the position in the x, y, z direction.

The fluid contacts are defined in relation to major faults and sand bodies.

Unconformity Map Generation : Once the features of a hypothetical or real field to be modelled have been decided, the top surface map will be digitised for linear multi-variate quadratic equation fitting. The resulting equation is used to regenerate the surface map to see the level of agreement.

Bed Generation : The coefficients for the first 'central' bed are entered. Successive beds are then entered as additions (upper beds) or subtractions (lower beds) to the parameters of the adjacent bed (with the exception of unconformity which should be entered fully).

[B] Rock and Fluid Property Definitions

[I] Lithology and Age Definition: Codes are assigned to each unique rock type which may be related to lithology-age. For example, if sequences from Cretaceous to Triassic are considered, then, for each age group, sand bodies, shales and carbonate rocks are assigned an identifying code. Unique codes are assigned to distinguish:

- reservoir and non-reservoir rocks,
- varying oil water contacts,
- age and lithologies, and

- reservoir rock properties.

[II] Reservoir Rock Specification : First, the depositional rock type description is entered, (e.g. channel, bar, shoal etc.) followed by:

(1) Porosity Definition : The mid point porosity for a particular rock type is defined by the following equation:-

$$A(X-dx)^2 + B(X-dx) + C(Y-dy)^2 + D(Y-dy) + E \quad (3)$$

where X and Y are the grid coordinates and A, B, C, D, E are the constants of the equation. Hence, the resultant porosities will display a regional trend. Also dx and dy shift parameters are used within the above equation to displace the origin in order to obtain a prescribed trend. If a trend is not desired, then A, B, C, D coefficients are set to zero and E is then equal to mean porosity. The value of E will then be randomised according to the values of the next two entries. Here the distribution is assumed to be normal and therefore a standard deviation value is required. If this latter quantity is not available, then rectangular distribution is used with the entry of limiting quantities.

Vertical porosity variation is considered with the following equation:-

$$\phi = \frac{[\text{Depth-Midpoint}] * f1}{f2} + \phi \quad (4)$$

If no upward or downward trend is required, f1 is set to zero and f2 is used as limits in a rectangular distribution, taking the mid-point value as the mean.

(2) Permeability : Permeability- porosity relationship is defined by:-

$$\text{Log} Y = -mX - C \quad (5)$$

where Y is permeability, X is porosity and C is a constant.

(3) Connate Water Saturation: This is defined by the following relationship:-

$$\text{Log} Y = -M * \text{Log} X + C \quad (6)$$

where $Y = (\text{Perm}/\text{Por})^{0.5}$ and X = Connate Water Saturation.

(4) Residual Oil Saturation : The equation describing the relationship of residual oil saturation with permeability and porosity is given by:-

$$Y = AX^2 + BX + C \quad (7)$$

where $Y = (\text{Perm}/\text{Por})^2$ and X = Residual Oil Saturation.

Other properties which are entered into the Set Up Module are contact angle and interfacial tension.

[III] Reservoir Fluid Specification : The following data are required: temperature gradient, surface temperature, oil gravity, water density, gas gravity, salinity of the formation water, compressibility of water and hydrocarbon

phases and solution gas oil ratio.

Data can be entered for reservoir as a whole or layer by layer using the codes assigned for individual beds.

EXPLORATION SIMULATION MODULE

This consists of Data Acquisition and Data Analysis Sub-Modules

[A] Data Acquisition Sub-Module (See Figure - 2)

First, the trainee obtains a contour map of the unconformity surface. A preliminary estimate of the reserve is now made from an assumed reservoir structure and the coordinates of the first well are decided.

[I] Characterisation of Wells: PRESEM requests the following input data from the user:

- name of the operating company and the well.
- X and Y coordinates of the well
- depth of the well
- drilling mud properties such as mud and mud filtrate resistivities at given temperatures.

PRESEM now produces an output data file which contains the following information for each bed intersected by the wells:-

. identity code, depth, dip, azimuth, thickness, minimum distances to the faults and/or pinch outs and information about the rock properties such as porosity, permeability and the irreducible oil and water saturations, volume of shale, oil water contact, calcium content.

. the variation of the petrophysical properties with depth is provided in the form of well logs and core analysis results.

[II] Log Generation : This is a sub-module which uses the data base generated in the previous sections to predict the electrical log values for R_t , R_{XO} , Gamma Ray, SP, Formation Density, Compensated Neutron Density, Sonic and Dipmeter. The equations used for this purpose are given in the Appendix[B]

At the end of this stage, the database for the well is ready for coring, well logs, RFT and Pressure Tests.

[B] Data Analysis Sub-Module

The following functions are included in this sub-module:

[1]Coring: Core data is provided at 10 meter intervals from top to bottom of the 'pay zone'. Data is provided for porosity, absolute permeability and shale content. A search is carried out to identify the reservoir forming rocks in the cored interval after which two phase oil water and gas oil relative permeabilities are predicted. The relationships for the prediction of the parameters listed in this section are given in Appendix-A.

[2]Electrical Well Logs: The procedure used here decodes the data obtained in Log Generation function of the Data Acquisition Submodule. The electrical logs are printed in one meter intervals. The available logs are R_t , R_{XO} , GR, SP, Formation Density, CNP, Sonic and Dipmeter. On completion of the listing, mud resistivity, mud filtrate resistivity and temperatures at which they were recorded are given. Graphical output can be obtained on a plotter similar to those provided by Schlumberger for 'quick log interpretation'.

The mathematical relationships used to derive the electrical log values are given in Appendix-B.

[3]RFT Pressure Tests: An interactive function is available for predicting the RFT pressures. The output from the program is formation pressure. At this stage, no attempt has been made to simulate drawdown and build-up responses. This is partly due to the complexity of simulating such a response but also because of the poor quality of RFT transient pressure data. The method of predicting pressures is given in Appendix-C.

[4]Pressure Tests: A transient well testing procedure is implemented with error validation and guidance against poor data. The function indicates whether the interval being tested will produce at the required rate and calculates the maximum rate attainable depending on the formation productivity, the fluid properties and the vertical lift performance of the production tubing.

The user is given the option of taking a fluid sample. Laboratory PVT analysis for oil and salt analysis for water are available.

The governing equations and physical relationships to obtain pressure response and other relevant data are given in Appendix-C.

TOOLS MODULE

Finally, exploration data obtained from successive drilling operations will be synthesised in the development and production plan. PRESEM present the operating company with a collection of tools to assist in this complex task(see Figure-4). The following functions are presently available in PRESEM.

- . Pressure Analysis
- . Log-Interpretation .
- . PVT Data Matching to represent the PVT behaviour of the *in situ* fluid by Equation of State(EOS).
- . Reservoir Characterisation at various scales.
- . Surface Facility Design
- . Reserve Estimation
- . Integrated Reservoir Performance Prediction
- . Economic Analysis.

[1] Pressure Analysis : Multi-rate pressure analysis techniques are applied to evaluate the well test data. Packages to predict physical properties such as permeability, skin factor etc can also be used at this stage. Currently, a pressure analysis package named WIPER by IPEC is used at Imperial College.

[2] Log Interpretation: Techniques utilised in PRESEM are based on the principles laid down by Schlumberger. A numerical procedure, similar to CORIBAND of Schlumberger is incorporated in PRESEM. Presently, this function utilises an Indonesian type equation for log interpretation.

[3] PVT Data Analysis: Component analysis of in place fluid as well as black oil parameters such as Formation Volume Factors, phase viscosities, Solution Gas Oil Ratios(SGOR) and Z factor as a function of pressure are provided for each well. Functions are available in PRESEM for regression based EOS and simulation of gravity induced compositional variations.

[4] Reservoir Characterisation : The database obtained from limited number of wells contain information starting from coring up to 3-D seismic information. *In situ* characteristics of the reservoir rock must be obtained from this data by recourse to geological interpretation and induction. Preparation of Fence Diagrams or CAD graphics might be required at this stage.

[5] STOIP Estimates : A Monte-Carlo type reserve estimation procedure is implemented to reach a statistical appraisal of the limited information about the reservoir. The basic requirement is the identification of distribution types for various reservoir parameters such as porosity, formation volume factors, area, length, thicknesses and the residual saturations.

[6] Reservoir Performance Prediction : SIMBEST supplied by Scientific Software Intercomp/U.S., PORES supplied by Robertson ERC Ltd/U.K., and a Compositional Simulation Procedure developed within the department are used to investigate the effects of various reservoir parameters and development schemes on hydrocarbon recovery. This is accompanied by analytical procedures and the integrated application results in an estimation of recovery factors and production strategy.

[7] Surface Facility Design : Functions are available in PRESEM for optimum design of surface facilities and pipe sizing.

[8] Economics : Computer packages, PECONO and PECONG developed within the department are used for economic analysis.

Once the alternative exploitation and development schemes which maximise the hydrocarbon recovery are evaluated a report must be prepared by the operating company to demonstrate to the financial backers the viability of the proposed scheme. Also, in the UK, a license must be obtained from the government to develop a field and a feasibility report called ANNEX-B must be submitted to the government for approval. The PRESEM projects culminates with the presentation of an ANNEX-B in a public hearing in which the members of the operating company present their case to an invited audience from the industry.

CASE STUDY - PRESEM FIELD

A case study is now presented based on a model field with North Sea type deltaic properties [4][5][6][7][8][9]. The field carries a selection of number of depositional environments commonly identified in reservoir modelling studies such as Marine Sands, Straight and Coalesced Channel Sands, Swamp/Lagoon, Bar Sands with Delta Top and Delta Front characteristics[10].

The licence area measures 7200 metres by 4800 metres covering about 8500 acres. Its top surface is given in Figure-5. This has a minimum depth of 2440 metres and a maximum depth of 2900 metres. The lowest elevation of the block appears along the North West-South East diagonal. The equation which describes this surface is given by:-

$$Z = Z_{\text{disp}} - [A(X+dX)^3 + B(X+dX)^2 + C(X+dX) + D + E(Y+dY)^3 + F(Y+dY)^2 + G(Y+dY) + H(X+dX)(Y+dy)] \quad (8)$$

where A = 0, B = -.00060258, C = -1.245642, D = 325.0, E = 0.0, F = -0.0153866, G = 1.847682, dX = 0, dY = 0 and H = 0.01122 with $Z_{\text{disp}} = 2787.94$.

Three faults are incorporated into this field example. Two of these run along the East-West direction close to the block boundaries, and one, in the North-South direction is tilted slightly to the left as shown from in Figure-6. Fault-1 is the oldest then followed by Fault-2, -3 and -4.

Other characteristics of the PRESEM Field are as follows:-

[1] Rock Characteristics : PRESEM's rock characteristics are typical to those of deltaic depositional environments where sand bodies of various origin are interbedded with shales. Special attention has been paid in describing the lithology of each rock where, for example, some sand bodies incorporate different grain sizes fining upwards or coarsening upwards sequence (typical of channel and shallow marine bar sands). As for the geological age of the formations, layers above the unconformity are considered to be deposited in Recent, Tertiary, Cretaceous and Upper Jurassic. The reservoir and non-reservoir rock bodies below the unconformity surface are from Mid Jurassic(Middle PRESEM) and Lower Jurassic(Lower PRESEM) bounded by Triassic red clays and shales with special identification code assigned for each rock. For this particular case study, about 27 rock units are included.

[2] Rock and Fluid Properties : Porosities, permeabilities and saturation tables exhibit lateral and vertical variations. Fluid properties are summarised in Table 1 for the respective reservoir layers.

I. Implementation of the Exploration Simulation Modules:

Drilling Program and *In Situ* Data Acquisition : The wells 'drilled' upon receipt of an approved AFE and well design are shown in Table-1 and Figure-7 with their coordinates (measure in units of 20 meters). The following database is now derived:-

[a] Mudlogs: An example of a typical mudlog is given in

Table-3 for the 'Wild Cat' well at location $x=160$ (3200 metres) and $y=120$ units (2400 metres). The top of the middle Jurassic layer is found to be located at 2631.56 metres and the top of the lower Jurassic at 2722.96 metres. Dark grey to black shales of the Triassic is found to be at 2929.26 metres. In the Middle Jurassic section, six sand bodies are interbedded with five light grey and silty shales. In the lower Jurassic section, six sandstone units with six shale layers are identified. Middle and Lower Jurassic layers are separated by 23 metres thick grey to dark grey carbonaceous shales, and the lowest sand body of the lower layer shows a thickness of 103 metres. Mudlogs obtained from other wells showed considerably more variation than the data obtained from this well which indicates the existence of discontinuities in the sand bodies.

[b] Logging and Coring: Figure-8 shows the relative permeability curves obtained from the wild cat well. The variation in the end points reflects the characteristics of the depositional environment where the upper part represents the middle sand units and the lower part the lower units. Figure-9 shows the capillary pressure distributions for the same well. Figure-10 shows the variation of porosity, permeability and volume of shale with depth for both sections. Figure-11 shows the results of wireline logs. GR, SP, RT, Rxo, CNL, Density and Sonic Log results are obtained for middle layers for the well drilled at location $x=15$ and $y=120$. Coring and well logging sub modules are implemented for each well.

[c] RFT and Well Testing : To determine the initial fluid pressures, RFT (Repeat Formation Tester) procedure is implemented for each well. The results of one of these tests is shown in Figure-12 for the wild cat well. The oil pressure gradient is determined to be 0.366 and 0.363 psi/ft respectively for the middle and lower layers. A multi-rate pressure build-up procedure is implemented for well testing where the first cycle (limited drawdown and build up) is used for clean up and the second cycle is used for build up. The results of this test (for the wild cat well) are given in Figure-13.

II. Implementation of the Tools Module:

The mudlog, wireline logs, core and well testing data are processed at this stage. A log interpretation procedure is used to determine the initial water saturations, porosities and saturations of invaded zones for each well (Figure-14). A procedure supplied by IPEC ltd, called WIPER is used to generate the $kk_r h$ from the well test data.

Figure 15 shows PVT properties for the same well for both the middle and the lower layers, consisting of the variation of B_o , B_g , R_s , μ_o and μ_g with pressure.

In the next stage a geological map of the reservoir will be generated from the information collated from each exploration well. A fence diagram is also prepared for this purpose.

[a] Fence Diagram : This technique (also called *panel diagram*) is used as an aid to characterise and generate a valid geological model of the reservoir in 3-dimensions where both structural and stratigraphical sections are shown on an isometric projection. An examination of the

permeability values obtained by methods described above from the core data and the lithology, leads to the following geological observations:-

. The beds are tilted at $4-5^\circ$ in the East-West direction. Some of these disappear as they hit the unconformity surface,

. Marine type sand bodies are observed in both middle and lower layers, first on the top of middle layers with calciferous, variable, fine to coarse grains.

. Channel sands are identified with fine-middle-coarse grains fining upwards. This is confirmed by porosities, permeabilities and well testing results. The depositional features typical to channel sands, such as convex base as viewed from the bottom with relatively wider top adds further weight to this conclusion. Bar sands are also identified with a similar grain distribution to that of channel sands.

. Non-reservoir rocks observed in this field are also typical of deltaic depositional environments with a lithology of light grey and silty shales. Thin coal streaks similar to Marsh/Swamp depositions are also observed. These extend along the field in East-West and North-South directions with a thickness varying from a few feet to tens of feet.

A fence diagram is prepared using some of the wells for the middle layers as shown in Figure-16 from which it is possible to identify the geological features mentioned above. During the course of the PRESEM exercise, complex fence diagrams are often prepared based on the exploration data. These use the information derived on the depositional environment, the relationships between vertical data (wells) and lateral continuity and scale rationalisations. Obviously, the validity of the geological model finally depends on the users engineering experience and judgement. This model is now used as the basis for fieldwise performance evaluations.

[b] STOIPP Estimates : There are several techniques for estimating the in place hydrocarbons. Some of these are based on mapping techniques which often result in different deterministic predictions. In many ways it is preferable to present the in place hydrocarbon reserves as a probabilistic estimate. For this purpose, PRESEM uses a method based on Monte Carlo analysis where statistical distributions are assigned to parameters forming the equation:-

$$V_{sc} = \frac{PS \cdot A \cdot h}{B_o} \quad (9)$$

where V_{sc} is the volume of oil at standard conditions, PS is $\phi \cdot (1 - Sw_1)$, ϕ is porosity, Sw_1 is initial water saturation, A is area, h is thickness and B_o is formation volume factor. The hydrocarbon reserve estimates are, then, plotted against cumulative probability as shown in Figure-17. In current usage the 90 % level represents *Proven* value, 50 % level represents *Proven+Probable* value and 10 % represents *Proven + Probable + Possible* value of reserves in MMM Stock Tank Barrel.

[c] The Final Stage of this exercise covers the use of various procedures to carry out surface facility design, reservoir simulation to investigate sensitivity effects of

various reservoir parameters on the field performance and economic analysis based on the current economic constraints. These aspects of PRESEM have not been included in this paper.

CONCLUSIONS

1. A computer aided teaching system (PRESEM) is presented. The system consists of software which is suitable for use on PC-DOS compatible computers.

2. The principal modules of PRESEM are:-

(a) Set Up Module by which the geometry, geology and rock and fluid properties of any reservoir model can be defined interactively by the supervisor.

(b) Exploration Simulation Module allows the trainees to 'drill' a number of wells on the field (the reservoir database defined by the Set Up Module)

(c) The Tools Module comprising a range of special applications software to allow a comprehensive technical and economical evaluation of the field.

3. A case study presented in this paper models a deltaic depositional environment typical to the North Sea and illustrates the use of PRESEM.

4. PRESEM's flexibility renders it suitable for application in specific or general training programmes in the oil industry.

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NOMENCLATURE

I. Capitals:

A: Area in Eq.8 and constant in Eqs.1 and 2.
 B: Constant in Eqs. 1 and 2.
 C: Constant in Eq. 1, 2 and 4.
 D: Constant in Eqs. 1 and 2.
 E: Constant in Eqs. 1 and 2.
 F: Constant in Eqs. 1 and A.2.
 G: Constant in Eqs. 1 and A.2.
 GR: Gamma Ray.
 H: Constant in Eqs. 1 and A.2.
 I: Constant in Eq. A.2.
 J: Constant in Eq. A.2.
 K: Permeability.
 M: Constant in Eq. A.4.
 N: Constant in Eq. A.4.
 OWC: Oil Water Contact.
 P: Pressure
 PPM: Parts per Million.
 R: Resistivity.
 S: Skin Factor, also used for Saturation.
 SGOR: Solution Gas Oil Ratio.
 SP: Spontaneous Potential.
 T: Temperature

TZ: Height of Transition Zone.

V: Volume

X: Coordinate Direction, also used as Permeability

Y: Coordinate Direction, also used as Permeability

Z: Depth

II. Small Letters:

a: Constant in FRF Equation.

dx: Shift in x-direction.

dy: Shift in y-direction.

f1: Constant in Eq. 3.

f2: Constant in Eq. 3.

h: Thickness.

k: Permeability.

m: Constant in FRF Equation.

r: Radius.

x: Coordinate Direction.

y: Coordinate Direction.

z: Depth.

III. Subscript and Superscript:

b: Bubble Point.

c: Capillary Pressure.

disp: displacement.

e: equivalent.

i: initial.

irr: irreducible.

m: Mud.

mf: Mud Filtrate.

o: Oil.

sh: Shale.

st: Standard.

w: Water(also used for Well).

xo: Invaded Zone.

IV. Greek :

α : Alpha.

β : Beta.

γ : Gamma.

ρ : Density.

Σ : Summation

ϕ : Porosity.

SI Metric Conversion Factors:

$$\text{API} (141.5/(131.5 + \text{API})) = \text{g/cm}^3$$

$$\text{bbl} \times 1.589\ 873\ \text{E-01} = \text{m}^3$$

$$\text{cp} \times 1.0\ \text{E-03} = \text{Pa.s}$$

$$\text{degrees} \times 1.745\ 329\ \text{E-02} = \text{rad}$$

$$\text{ft} \times 3.048\ \text{E-01} = \text{m}$$

$$\text{F} (^\circ\text{F}-32)/1.8 = ^\circ\text{C}$$

$$\text{psi} \times 6.894\ 757\ \text{e}+00 = \text{kPa}$$

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APPENDIX A-Physical Relationships Used in the Procedures

Described in this Appendix are the equations and relationships used in the program to obtain some of the physical parameters which are as follows:-

[1] Mud Filtrate or Formation Water Resistivity : The resistivity in Ω -meter, of a sodium chloride solution in terms of solution temperature, in degrees Fahrenheit, and salinity in parts per million, is given by the equation:-

$$R = 20.0 \exp (-0.43089016 * Z) \quad (\text{A.1})$$

$$Z = X - 1.316(X - Y) \quad (\text{A.1a})$$

with X and Y given as;

$$X = -6.97 \ln(0.002T) \quad (\text{A.1b})$$

$$Y = A * (4 \ln(\text{PPM}) + B * (3 \ln(\text{PPM})) + C * (2 \ln(\text{PPM})) +$$

$$D + \ln(\text{PPM}) + E) \quad (\text{A.1c})$$

whose constants can be predicted using curve fitting procedure of charts given in Ref[2].

[2] Mud Filtrate or Formation Water Salinity:

$$\ln(\text{PPM}) = FU^4 + GU^3 + HU^2 + IU + J \quad (\text{A.2})$$

where U is given by $U = V - 0.76(V - W)$ whose constants can be obtained from Ref[2].

[3] Water Density : The density of a saline solution at a particular temperature and pressure is given by the following relationship:-

$$\text{Density} = \left\{ \sum_{M=6}^X \text{Temp}^{(M-6)} \right\} + 7.3X10^{-7} \quad (\text{A.3})$$

where M = 6, and X is given by

$$X = \sum_{N=8}^{\text{Const}((M-1)*8+N) * (\text{Pressure}/1000)^{(8-N)} * 10^{-12}} \quad (\text{A.3a})$$

where Const is an array. These equations are obtained from polynomial fit program with data from Ref[24][25].

[4] Shale Volume :

$$\log(V_{sh}) = -0.267 * \log(\phi K) - 0.559 \quad (\text{A.4})$$

This is purely empirical equation with no particular meaning but used to obtain realistic values for shale content.

[5] Irreducible Water Saturation: The water saturation above the transition zone is given by the following equation:-

$$\log(S_{w,irr}) = (\log\left(\left(\frac{K}{\phi}\right)^{0.5} - S_2\right) / S_1) \quad (\text{A.5})$$

[6] Height of Transition Zone :

$$TZ = P_{cmax} / \Delta G \quad (A.6)$$

where ΔG is the density difference between water and hydrocarbon phase.

$$P_{cmax} = (S_{wcJ} * O1 * O2) / (K / \phi^{0.5}) \quad (A.5a)$$

$$\text{Log } S_{wJ} = -0.4 - 1.9 * \text{Log}(S_{wirr} + 0.05) \quad (A.5b)$$

[7] Water Saturation Within The Transition Zone :

$$\text{Log } S_w = -0.4 - 1.9 * \text{Log}(S_{wirr} + 0.05) \quad (A.6)$$

$$P_{cJ} = (P_{cO1} * O2) / (K / \phi^{0.5}) \quad (A.6a)$$

$$P_c = \Delta G * \text{Height Above OWC} \quad (A.6b)$$

[8] Water Saturation in the Invaded Zone: In the invaded zone the water saturation is calculated from the residual oil saturation which is given by the equation:-

$$S_{or} = (R2 + (R2^2 - 4 * R1 * (Q1 - (K/\phi)^{0.5}))^{0.5}) / (2.0 * R1) \quad (A.7)$$

$$S_{xo} = 1.0 - S_{or} \quad (A.7b)$$

[9] Relative Permeability to Oil and Water: For this particular exercise the following relationships are used [11]

$$U_{pO} = 16 * S_o^2 * (S_o - S_{or})^3 * (1 - S_{or}) \quad (A.8a)$$

$$D_O = 2.0 * S_o^2 * (2 - 3 * S_{or}) + 3 * S_o * S_{or} * (3 * S_{or} - 2) + S_{or} * (4 - 5 * S_{or})^2 \quad (A.8b)$$

$$U_{pW} = 16 * S_w^2 * (S_w - S_{wc})^3 * (1 - S_{wc}) \quad (A.8c)$$

$$D_W = 2.0 * S_w^2 * (2 - 3 * S_{wc}) + 3 * S_w * S_{wc} * (3 * S_{wc} - 2) + S_{wc} * (4 - 5 * S_{wc})^2 \quad (A.8d)$$

$$k_{ro} = \frac{U_{pO}}{D_W}, k_{rw} = \frac{U_{pW}}{D_W} \quad (A.8e)$$

APPENDIX B-Relationships Used for Electrical Logs

The equations to generate the electrical log data are as follows:-

[1] R_t and R_{xo} are calculated using Indenosia Equations:-

$$R_t = \left\{ \frac{1}{\left(\left(\frac{1}{F \cdot R_{mf}} \right)^{0.5} + \left(\frac{V_{sh}}{R_{sh} \cdot 0.5} \right) \right) S_w^{0.5n}} \right\}^2 \quad (B.1)$$

$$R_{xo} = \left\{ \frac{1}{\left(\left(\frac{1}{F \cdot R_{mf}} \right)^{0.5} + \left(\frac{V_{sh}}{R_{sh} \cdot 0.5} \right) \right) S_{xo}^{0.5n}} \right\}^2 \quad (B.2)$$

where F is the formation factor, R_w is the connate water resistivity, V_{sh} is the shale fraction, R_{sh} is the shale resistivity, S_w is the water saturation, R_{mf} is the mud filtrate resistivity, S_{xo} is the water saturation in the invaded zone and n is the saturation exponent.

The formation factor F is predicted using $F = \frac{a}{\phi^m}$.

[2] The Gamma Ray Log assumes constant radioactivity within the shales for this exercise and it is taken as proportional to the shale fraction and inversely proportional to the formation density. The Spontaneous Potential (SP) is calculated from:-

$$PSP = -K \text{Log} \left(\frac{R_{xo}}{R_t} \right) - 2 \alpha K \text{Log} \left(\frac{S_{xo}}{S_w} \right) \quad (B.3)$$

where K is the usual coefficient of the electrochemical SP, α is the SP reduction factor equal to PSP/SSP . K is calculated from $K = 60 + 0.133 T$ where T is the temperature in Fahr. Formation Density and Compensated Neutron Porosity are calculated from the porosity, shale fraction and calcium content from a curve fit of Schlumberger Chart CP-1D. They are also corrected for hydrocarbon density. Similarly, the Sonic Log is calculated with variation of shale transit time proportional to depth to account for compaction. After generation of log values, they are randomised using a Monte-Carlo type procedure.

APPENDIX C-Equations Used for RFT and DST Procedures

The physical relationships used for RFT and DST procedures are listed as follows:-

[1] Formation Productivity : It is assumed for this exercise that the formation productivity is constant and equal to a semi-steady state productivity index with a radius of influence of 250 ft.

$$PI = \frac{0.007082 * kh}{\beta \mu (\ln(\frac{r_e}{r_w}) - 0.5 + S)} \quad (C.1)$$

where kh is permeability thickness product, β is formation volume factor, μ is viscosity, r_e is drainage radius, r_w is well radius and S is skin factor.

[2] Pressure Differential Across the Tubing :

$$\text{Energy Loss} : W_f = 4fv^2 \frac{h}{2gD} \quad (C.2)$$

where v is the average mixture velocity over the tubing interval Δh , D is the internal diameter of the tubing, f is the factor determined empirically. Using Pettmann and

Carpenter modification to the energy equation:-

$$144 \frac{\Delta P}{\Delta h} = \bar{\rho} + \frac{\bar{K}}{\bar{\rho}} \quad (C.3)$$

where P (psi) is the pressure drop over a vertical interval h (ft), $\bar{\rho}$ is the average density of the fluid in this interval (lb/cft), and \bar{K} is defined by the following equation:-

$$\bar{K} = \frac{fq^2 M^2}{7.413 \times 10^{10} D^5} \quad (C.4)$$

where q is the liquid production rate, M is the total mass of gas associated with 1 bbl of stock tank liquid (lbs), D is the inside diameter of the tubing (ft) and f is the energy loss factor which is calculated using the following fit equations:-

$$\text{If, } \left\{ \frac{qm}{D} * 10^{-6} \right\} < 2.7 \text{ then } f = 0.0301171 * \left\{ \frac{qm}{D} * 10^{-6} \right\}^{-1.62562} \quad (C.5a)$$

$$\text{If, } \left\{ \frac{qm}{D} * 10^{-6} \right\} > 2.7 \text{ then } f = 0.00784986 * \left\{ \frac{qm}{D} * 10^{-6} \right\}^{0.295385} \quad (C.5b)$$

[3] Pressure Response to Well Testing: Constant terminal rate solution is used as a basis in the program. Also considered in the pressure response predictions is the effects of boundary conditions due to flow barriers like faults and pinch outs. The equation characterising the pressure response for these conditions is as follows:-

$$\frac{2\pi kh}{q\mu} (P_i - P_{wf}) = P_d(T_d) = \frac{1}{2} \ln \left\{ \frac{4T_d}{\gamma} \right\} + \frac{1}{2} \sum_{j=1}^n \text{Exp}_i \left(\frac{\phi u c a^2}{4kt} \right) \quad (C.6)$$

When more than one rate is used, superposition theorem is used. The general form of the superposition theorem implemented in the procedure is given as follows:-

$$P_w = P_i - \frac{70.6\mu B_o}{kh} \sum_{j=1}^n \Delta q_j P_d(T_d - T_{dj-1}) \quad (C.7)$$

A check is carried out to ensure that the calculated pressure response is exact (within the bounds of theory and assumptions).

[4] PVT Data : Bubble point pressure is predicted using the following equation:-

$$\text{Log} P_b = a + b + \text{Log} P_b^* + c(\text{Log} P_b^*)^2 + \dots \quad (C.8)$$

where

$$P_b^* = \left\{ \frac{\text{GOR}}{\gamma_g} \right\}^{a1} \frac{T^{a2}}{\text{API}^{a3}} \quad (C.8a)$$

where a, b, c,.... and a1, a2, a3 are the constants determined by nonlinear regression procedure. P_b is the bubble point pressure, Gor is the producing gas oil ratio, γ is the average specific gravity, T is the reservoir temperature, API is the stock tank oil gravity and P_b^* is the 'correlating number' to calculate the bubble point pressure.

Similarly, oil and gas Formation Volume Factors are calculated using the following equations:-

$$B_{ob}^* = \text{GOR} \left\{ \frac{\gamma_g}{\gamma_o} \right\}^{a1} + a2 * T \quad (C.9)$$

$$\text{Log}(B_{ob} - 1) = a + b * \text{Log} B_{ob}^* + c(\text{Log} B_{ob}^*)^2 + \dots \quad (C.9a)$$

and for gas, $B_g = 0.15875 \frac{Z}{P} (T + 459.67)$ where Z is calculated using Ref[18]. The pressure is calculated using the following relationship:-

$$P = P_{owc} - (D_{owc} - D) * \rho_{res} * 0.433 \text{ where}$$

$$\rho_{res} = \frac{\rho_{ost} + \text{GOR} * \gamma_g * 0.000217}{\beta_o}$$

$$\rho_{ost} = \frac{141.5}{\text{API} + 131.5} \text{ and}$$

$B_o = B_{ob} - (P - P_b) * C_o$ where C_o is oil compressibility. Using these the following quadratic Pressure equation is obtained whose required root is predicted as follows:-

$$P = \frac{(-B - (B^2 - 4AC)^{0.5})}{2A} \quad (C.10)$$

where

$$A = C_o,$$

$$B = -[(P_z + (D_{owc} - D_z) * W_g) * C_o + P_b * C_o + B_{ob}], \text{ and}$$

$$C = (P_z + (D_{owc} - D_z) * W_g) * (B_{ob} + P_b * C_o) - (D_{owc} - D) * (\rho_{ost} + 0.000217 * \text{GOR} * \gamma_g) * 0.4333$$

Oil and gas viscosities are calculated using Ref[19].

Table 1
Fluid PVT Data for Each Unit

	Middle PRESEM	Lower PRESEM	Units
°API	36	37.3	
SGOR	807	893	SCF/STB
Gas Grv.	.980	.976	
Salinity @ 60 F	24000	19000	PPM
Comp	17.2e-6	20e-6	1/psi

Table 3

Mudlog [X = 160, Y = 120]	
<p>OTOP OF PESEM MIDDLE AT : 2631.56 *****</p> <p>SANDSTONE,CALCIFEROUS,VARIABLE,F-C GRAIN</p> <p>2644.26 : SHALES,LIGHT GREY,SILTY</p> <p>2651.22 : SANDSTONES,F-M-C GRAIN,FINING UP</p> <p>2657.26 : SHALES,LIGHT GREY,SILTY</p> <p>2664.56 : SANDSTONES,F-M-C GRAIN,FINING UP</p> <p>2670.26 : SHALES,LIGHT GREY,SILTY</p> <p>2670.53 : SANDSTONES,F-M-C GRAIN,FINING UP</p> <p>2677.26 : SHALES,LIGHT GREY,SILTY</p> <p>2677.63 : SANDSTONES,F-M-C GRAIN,FINING UP</p> <p>2684.26 : SHALES,LIGHT GREY,SILTY</p> <p>2686.46 : SANDSTONES,CALCIFEROUS,M GRAIN</p> <p>2699.06 : SANDSTONES,CALCIFEROUS,F-M GRAIN</p>	<p>OTOP OF PESEM LOWER AT : 2722.06 *****</p> <p>GREY-DARK GREY CARBONACEOUS SHALES</p> <p>2746.26 : SILTSTONES AND CLAYS WITH THIN COAL STREAKS</p> <p>2760.26 : SANDSTONES,CALCIFEROUS,M-C GRAIN, FINING DOWN</p> <p>2779.26 : SANDSTONE,M-C GRAIN,POORLY SORTED</p> <p>2789.26 : SHALES,LIGHT GREY,SILTY</p> <p>2789.46 : SANDSTONE,M-C GRAIN,POORLY SORTED</p> <p>2797.26 : SHALES,LIGHT GREY,SILTY</p> <p>2797.45 : SANDSTONE,M-C GRAIN,POORLY SORTED</p> <p>2805.26 : SHALES,LIGHT GREY,SILTY</p> <p>2816.06 : SANDSTONE,M-C GRAIN,POORLY SORTED</p> <p>2817.26 : SHALES,LIGHT GREY,SILTY</p> <p>2826.06 : SANDSTONE,M-C GRAIN,POORLY SORTED</p> <p>2829.26 : DARK GREY TO BLACK SHALES,MOD CARBONACEOUS</p> <p>TOTAL DEPTH : 3500.00</p>

Table 2
Well Coordinates
(1 Unit = 20m)

X	Y
160	120
90	30
165	60
255	30
330	60
270	180
195	165
90	195
15	120
280	120

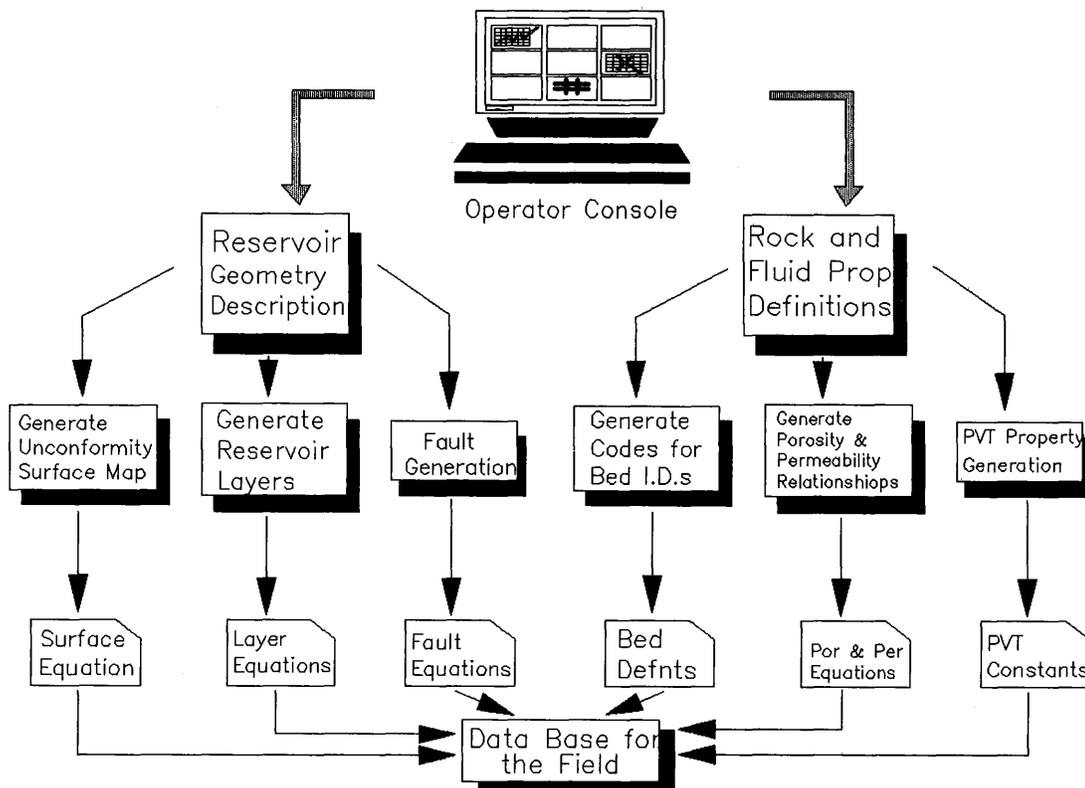


Fig. 1 - Set Up Modules

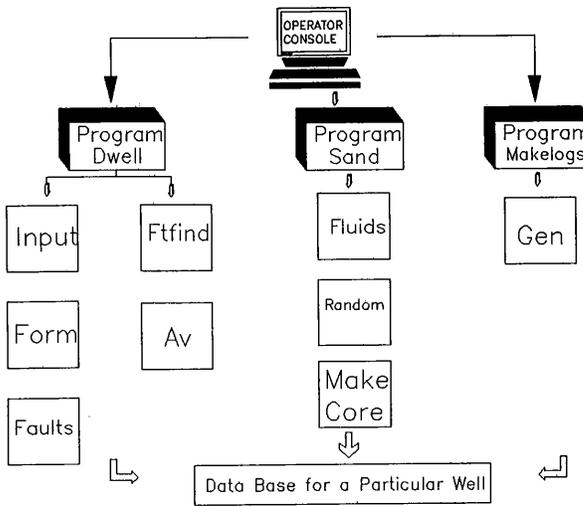


Fig. 2—Data Acquisition Sub Module

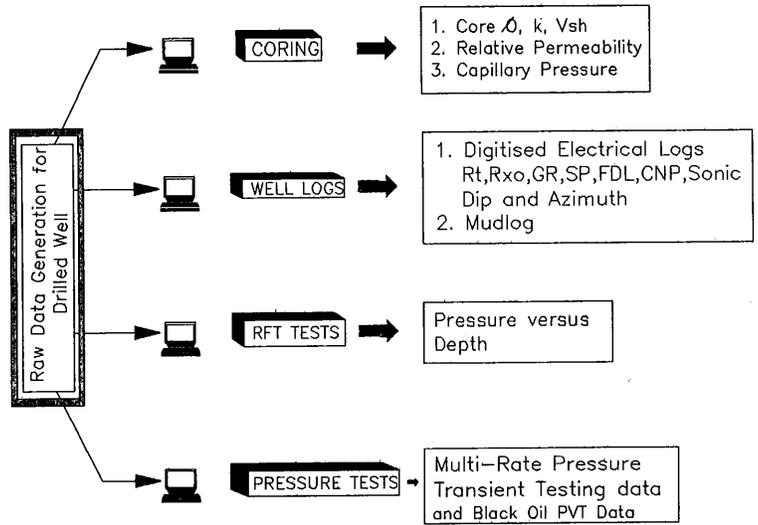


Fig. 3—Data Analysis Sub Module

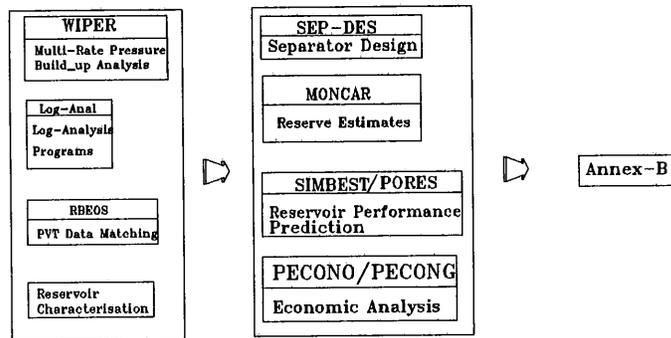


Fig. 4—Tools Module

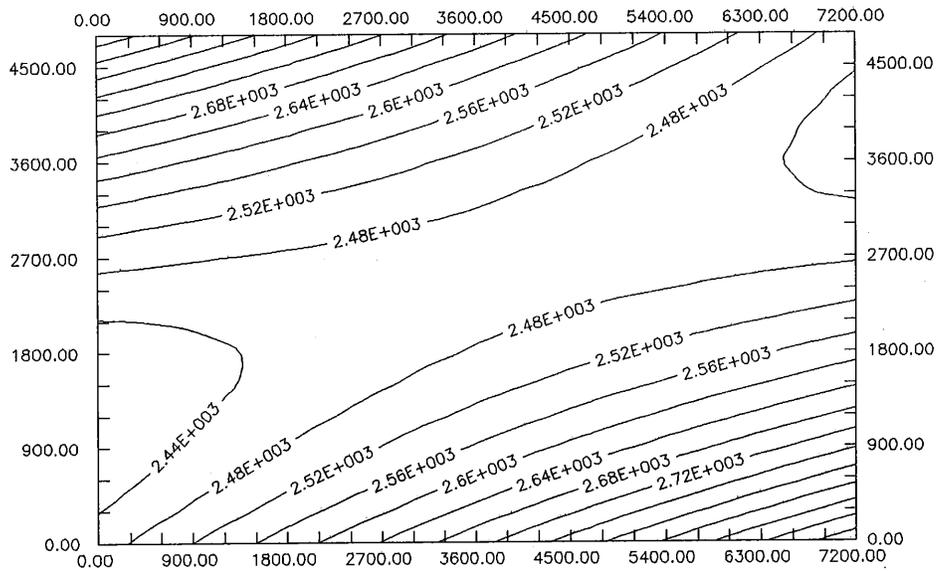


Fig. 5—PRESEM Field Top Surface Map

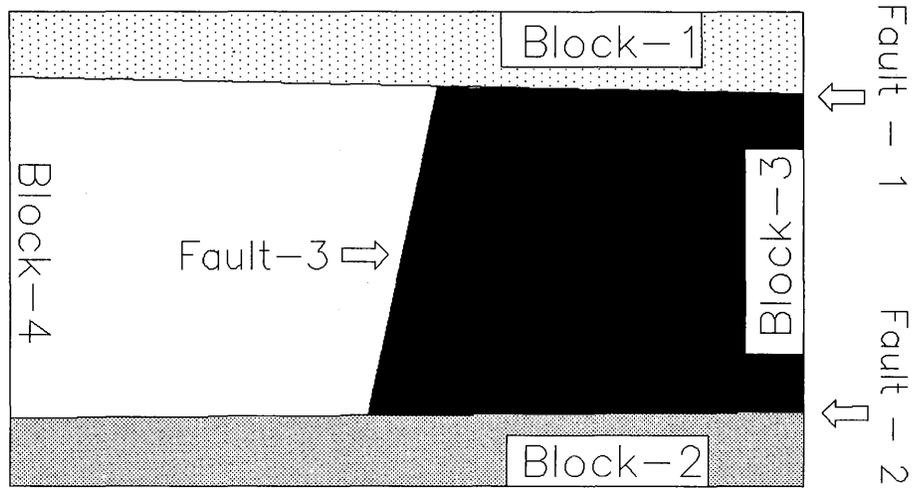


Fig. 6—PRESEM Field Fault Configuration

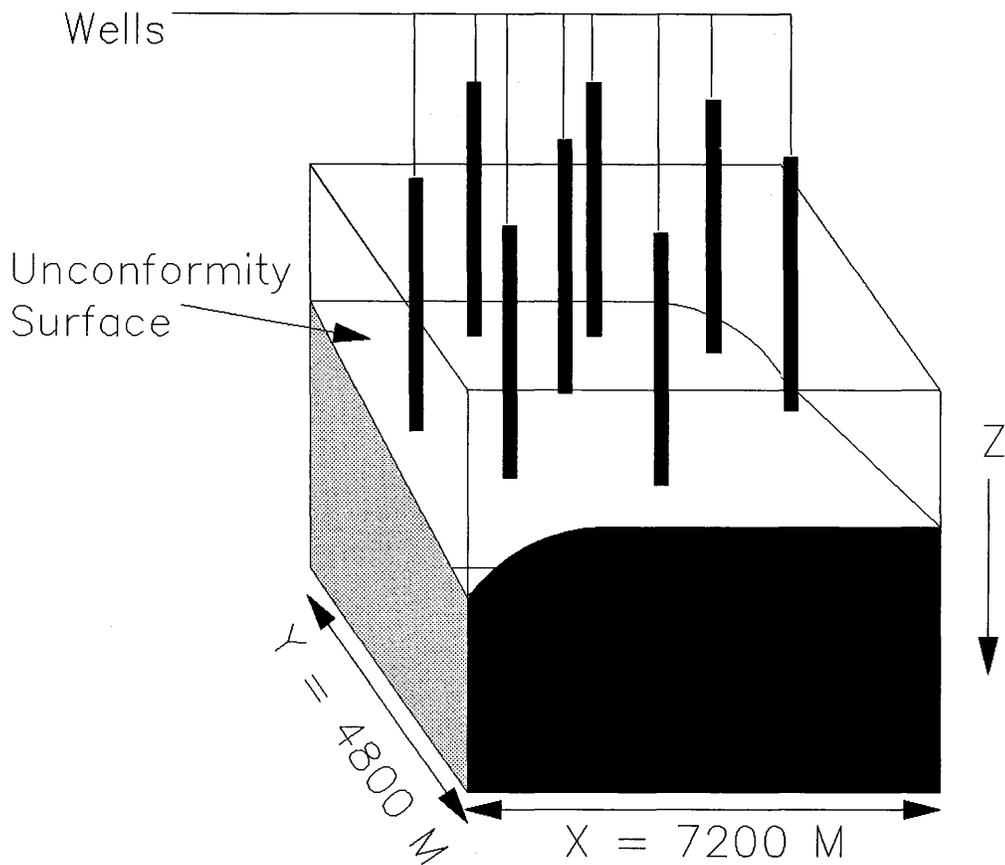


Fig. 7—Position of Wells 'Drilled'

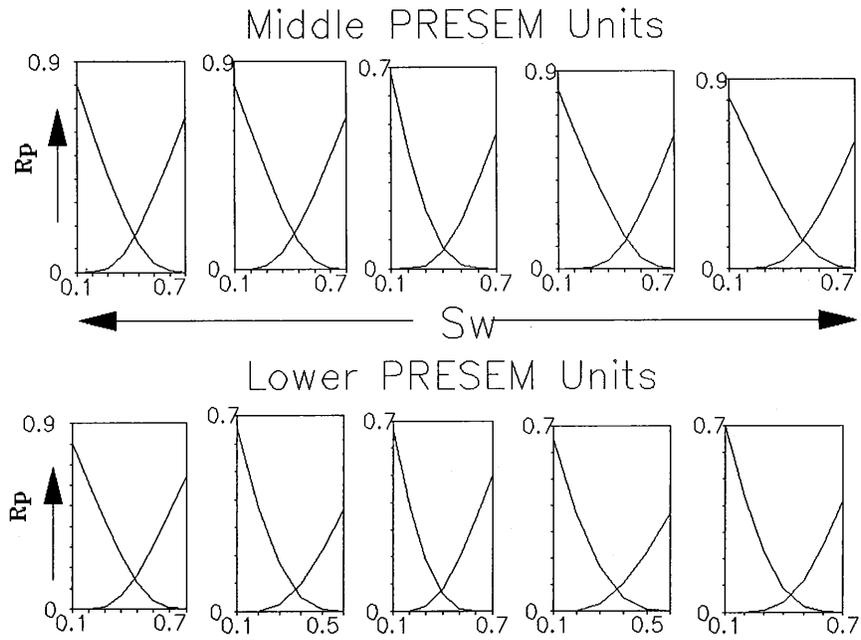


Fig. 8—Example Saturation Table Outputs

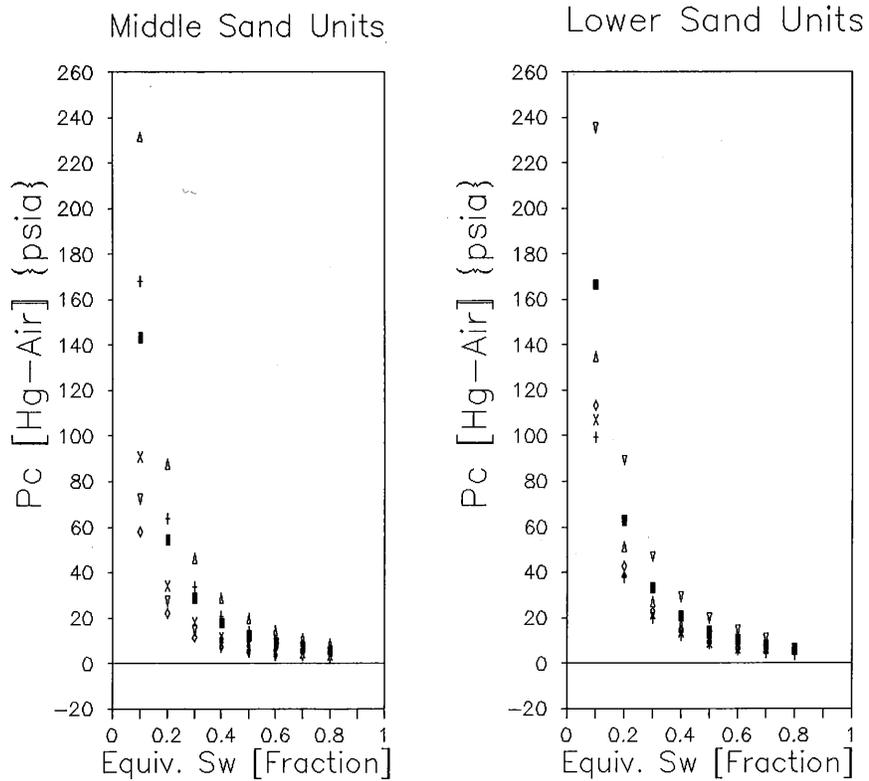


Fig. 9—Pc Curves [x=160,y=120]

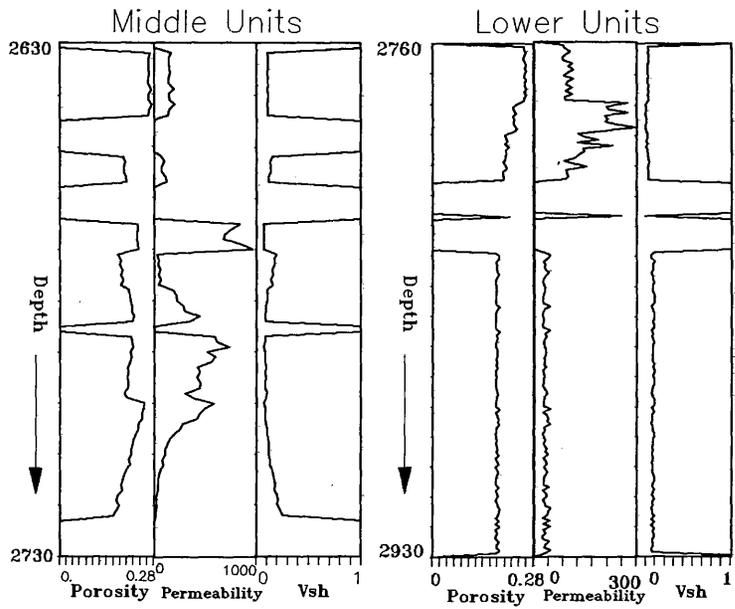


Fig. 10—Core Data for x=16, y=120

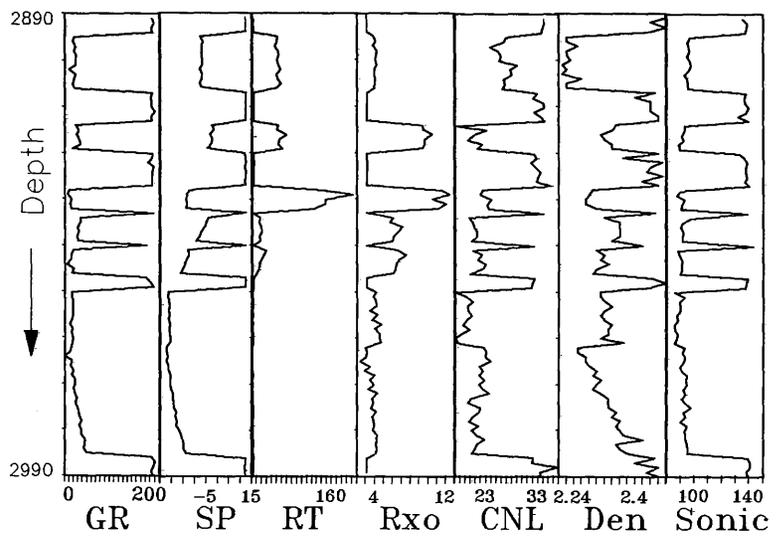


Fig. 11—Wireline Log Data for Middle PRESEM[x=15,y=120]

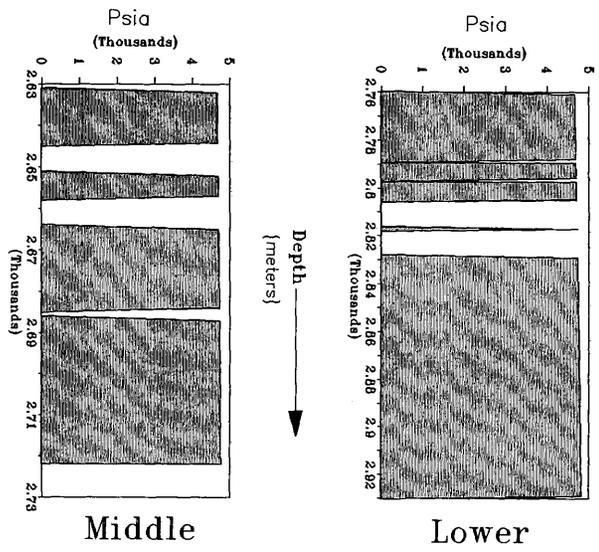


Fig. 12—RFT Pressures [x=160, y=120]

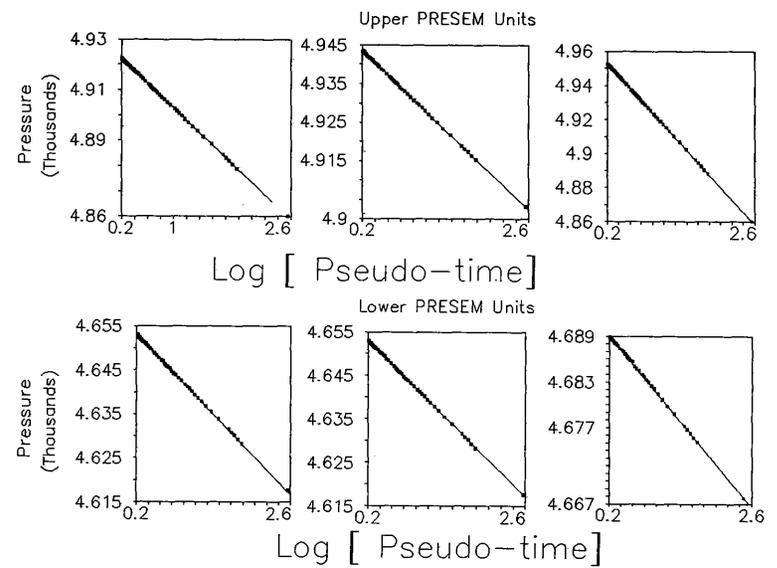


Fig. 13—DST Results From Different layers (Wild Cat)

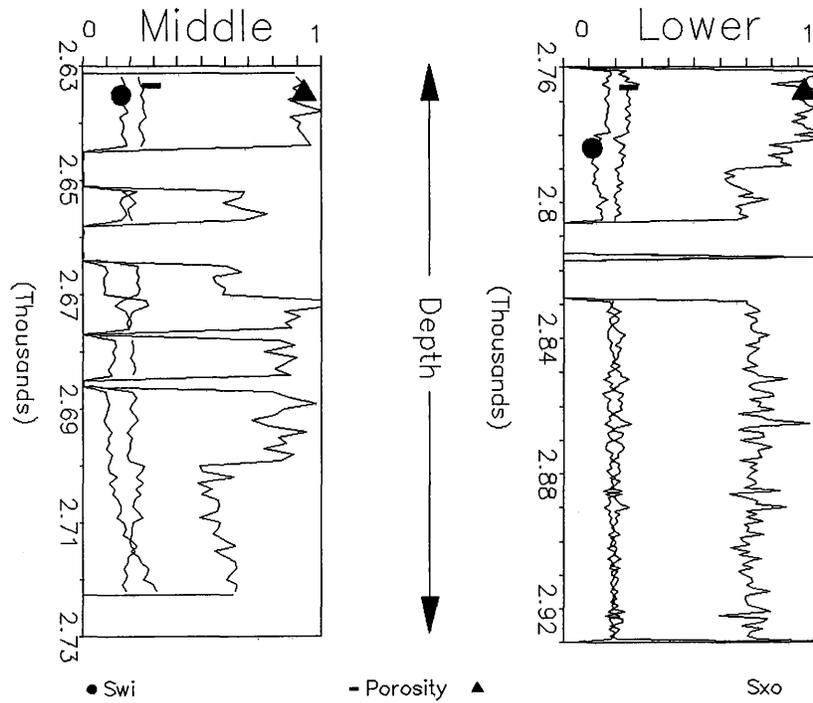


Fig. 14—Log Interpretation Results (Wild Cat)

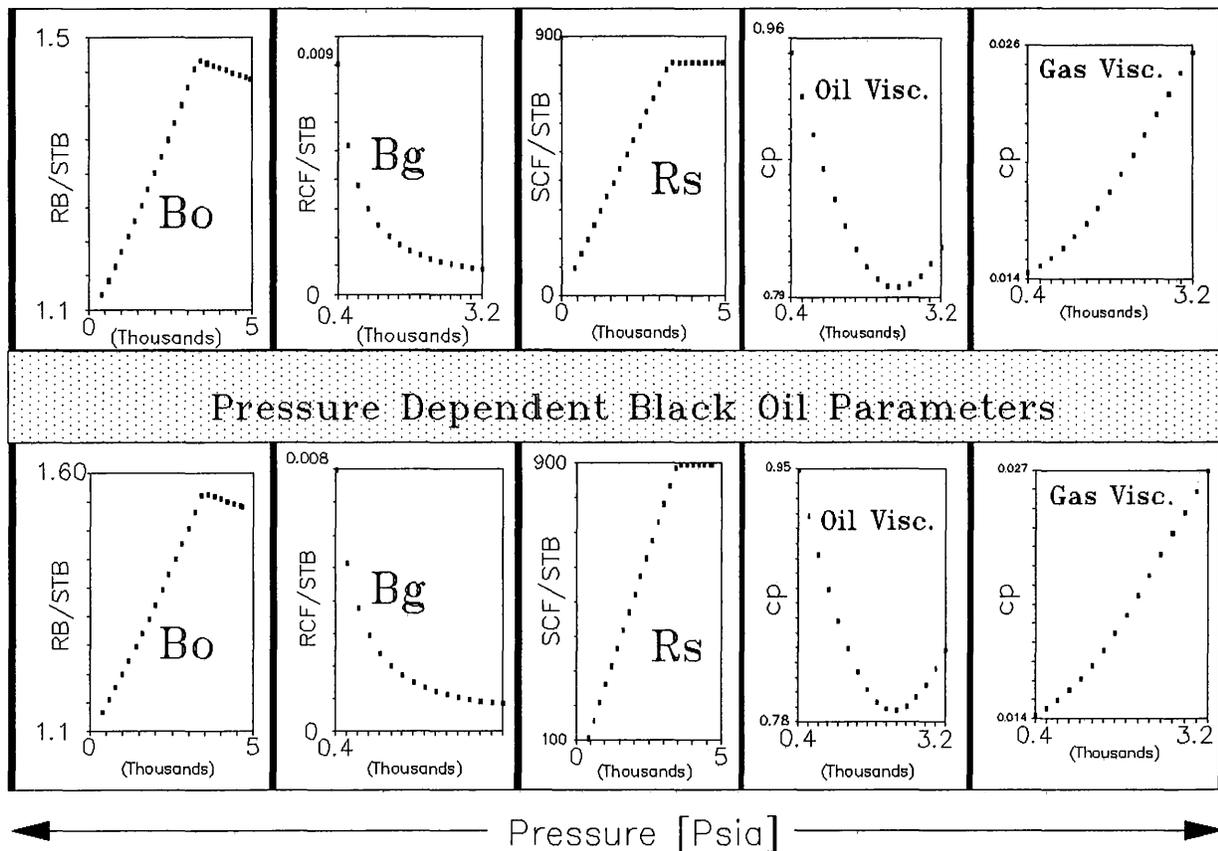


Fig. 15—PVT Data for Middle and Lower PRESEM [Wild Cat]

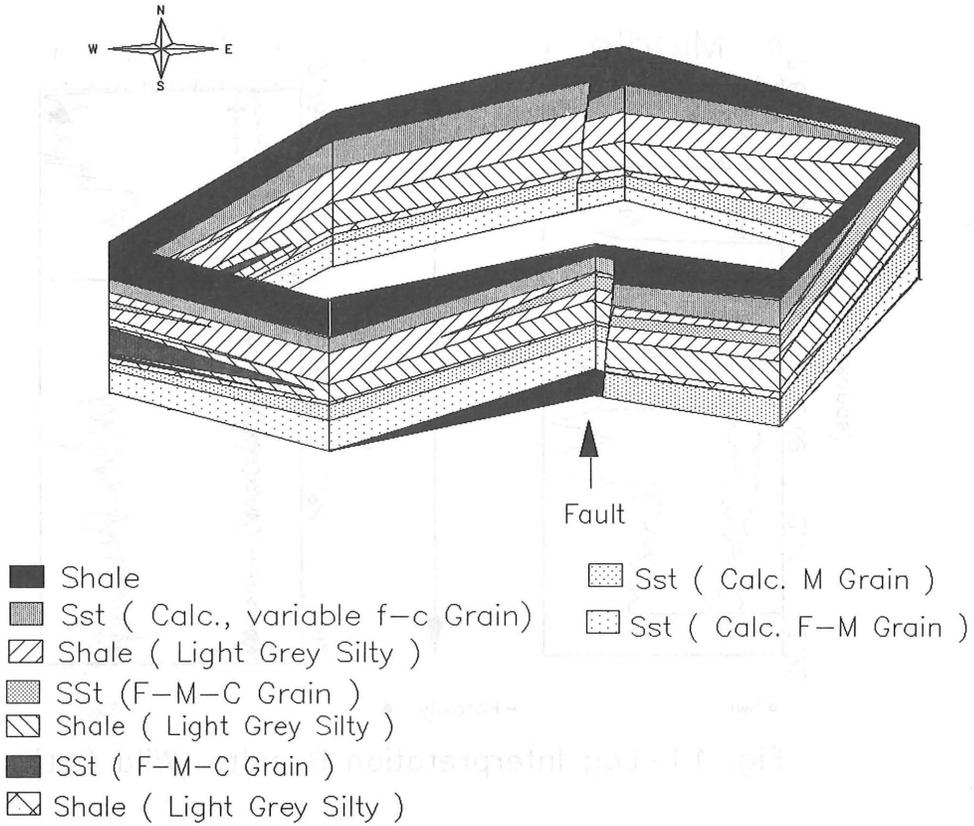


Fig. 16—Fence Diagram of Middle Pesem Units

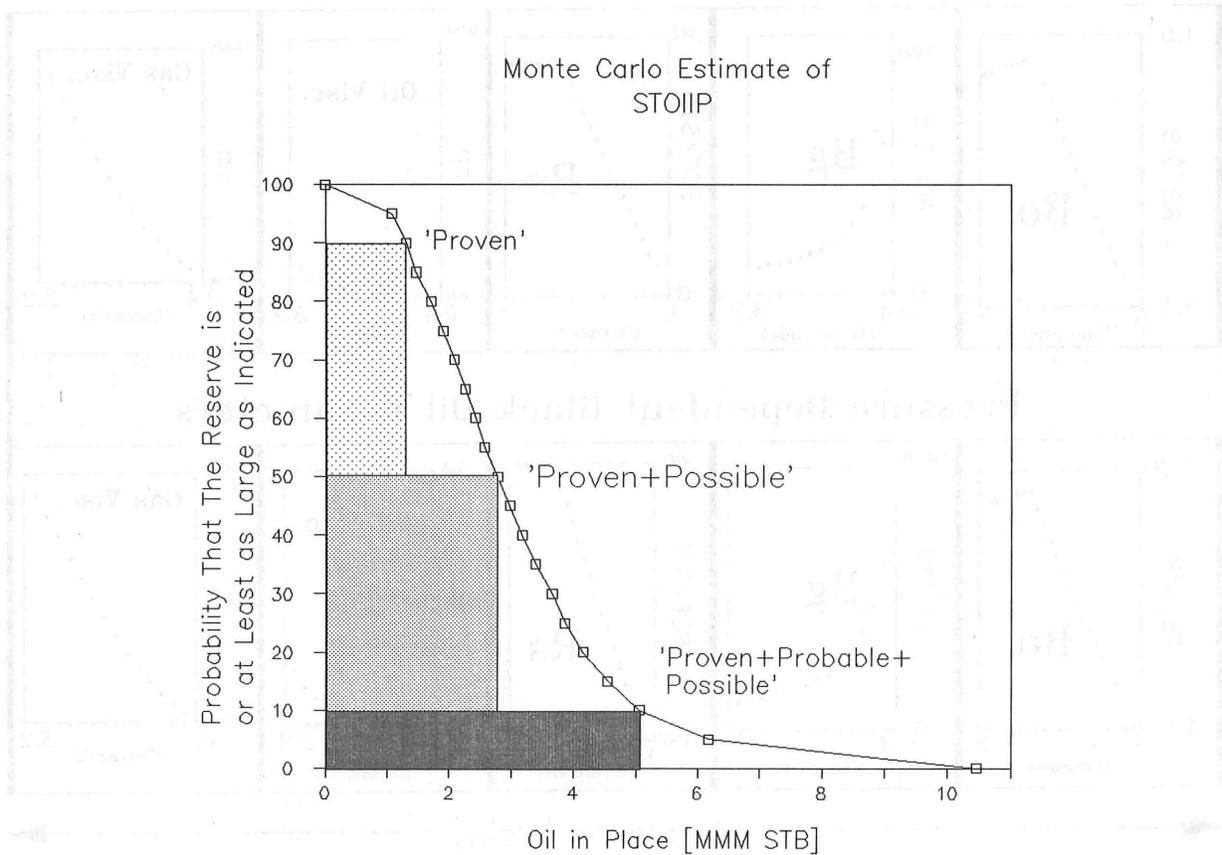


Fig. 17—Monte Carlo Estimate of Oil in Place