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SEISMIC MODELS OF GEOPRESSURED NATURAL GAS RESERVOIRS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

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Norman, Oklahoma

1983

SEISMIC MODELS OF GEOPRESSURED NATURAL GAS RESERVOIRS

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DEDICATION

This research effort is dedicated to the memory of Dr. John A. E. Norden, late University of Oklahoma Professor of Geology and Geophysics. Dr. Norden supported my graduate studies in Geophysics by hiring me as a seismic field assistant. I shall cherish the experience I gained through working with him. His sense of humor, which he typically demonstrated over a cup of coffee after work, should serve as a good example for everyone.

Following completion of my Master's degree in Geophysics, Dr. Norden suggested that I pursue a Ph.D. degree in Petroleum and Geological Engineering, and recommended me to the department.

Professor Norden brought true meanings to each of the words: education, teaching, research, and invention. His unselfish creativity and meticulous nature were perhaps best exemplified through his teaching and invention of the Seismic Catapult Gun.

In conclusion, Dr. John A. E. Norden was the type of educator and friend that one meets "once in a lifetime."

ACKNOWLEDGMENTS

The author is extremely grateful to Dr. Donald Menzie, Dissertation Committee Chairman, who supervised this research effort, taught me Petroleum Engineering courses, and encouraged me throughout the completion of this degree. I appreciate his "after hours" help and comments.

Thanks must also be extended to Dr. Robert DuBois, who reviewed the manuscript and offered constructive criticism and helpful suggestions. I am also grateful to Dr. Kenneth Luza, Dr. Edward Blick and Dr. John Morris, for their critical reviews and comments regarding the topic.

Next, I wish to thank Don Robinson, President of Oklahoma Seismic Corporation, who generously provided use of his equipment and facilities for this project. I also would like to acknowledge Richard Murnan and Harold Booker, for their help in constructing the seismic models.

Furthermore, I appreciate my parents for their unyielding support throughout my graduate studies, including completion of the Ph.D. degree.

Finally, I would like to thank my wife, Dr. Sue-Jane Lin, for her good example, constant encouragement, love and understanding, undenying support and assistance in preparing the manuscript.

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ABSTRACT

SEISMIC MODELS OF GEOPRESSURED NATURAL GAS RESERVOIRS

BY: CHARLES D. LEWIS

MAJOR PROFESSOR: DONALD E. MENZIE, Ph.D.

In order to study the seismic signatures of abnormally pressured sections, three different reservoir traps were modeled using a 40-Hz, zero-phase, Ricker wavelet and a two millisecond sample rate. MODEL A, CASES 1-2 involved a typical Oligocene sequence of the Gulf Coast Province with discrete lenticular sands encased in shales at depths of 5,000-5,500 feet. In CASE 1, the sands were assumed to be geopressured, while in CASE 2, the sands were normally pressured. MODEL B, CASES 1-2 involved abnormally and normally pressured channel sands, representative of the Pennsylvanian sequences in the Mid-Continent, encased in shales at depths of 12,500-13,100 feet. Finally, MODEL C, CASES 1-4 represented a typical Miocene sequence of the Gulf Coast with a growth fault reservoir containing interbedded tight sands and shales and a single gas sand upthrown to the fault and with a relatively thick sand accumulation downthrown to the fault. Depths ranged from 7,000-7,800 feet. Variations in reflection coefficient, polarity, amplitude, frequency, travel-time thickness and seismic waveform character were studied for each of the above-mentioned

models. It can be concluded that synthetic seismic models are useful in aiding in the prediction of geopressured gas zones, thereby reducing exploratory and developmental drilling costs as well as saving human lives.

CHAPTER I

INTRODUCTION

Today's engineer is faced with many problems in field developmental and exploratory endeavors. The search for more difficult targets, due to many of the "easy" structurally-controlled reservoirs having already been discovered, has led to increased emphasis on new stratigraphic and structural-stratigraphic plays. Also, decreased gas prices has caused many companies to reasses their leasehold properties before staking wells. Finally, new pricing incentives for deep hydrocarbons has resulted in companies keeping more abreast of new completion techniques in order to maximize their profits.

A net result of the above reasoning is that the oil and gas industry is searching for deeper hydrocarbon traps, some structural and others stratigraphic, and is looking for oil and gas in lithologies which ten years ago were considered taboo and of minimal importance as potential reservoirs. Today, the drilling success of an engineer in these complex "new" structural-stratigraphic reservoirs demands the use of up-to-date seismic methods (Ausburn, Nath, Wittick, 1978)[5].

Seismic anomaly mapping has resulted in numerous wildcat discoveries and successful field development wells as a result of the engineer and geophysicist being able to relate seismic character to porosity and lithologic changes in the reservoirs, thereby mapping vertical and lateral extents of hydrocarbons. Furthermore, improvements in drilling methods have allowed industry to drill deeper and faster than ever before.

Despite all these scientific and engineering advances, blowout prevention and control remain as significant problems, and these hazards will probably increase as deeper, more highly-pressured reservoirs are sought.

> The largest concentration of deep drilling rigs in the world today is in the Cyril Basin, deep in the Anadarko Basin of southwest Oklahoma. More than ninety wells are drilling or testing in this area of 200 square miles...The Cyril Basin is actually a sub-basin at the southeast end of the Anadarko Basin...Drill bits and other equipment at 3-4 miles down the hole may be subjected to temperatures above 300° F. Downhole pressures from clar or trapped gas can be enormous---over 20,000 psi (McCaslin,[27] 1982).

In order to more fully understand abnormal pressures, it is necessary to examine several definitions:

(1) Dickinson[10] (1953) was one of the first authors to introduce the concept of <u>geopressures</u> as ". . . any pressure which exceeds the hydrostatic pressure of a column of water containing 80,000 ppm total solids."

(2) Stuart[35] (1970) introduced a unique rock classification based upon pore-fluid pressures as

follows: "hydropressures, in which pore-fluid pressures are generated by the weight of the overlying waters and geopressures, generated by a pressuring source greater than waters."

(3) Timko, Gons, Grittman, and Rees[36] (1971) stated: "Formation pressure that exceeds the calculated hydrostatic pressure" is abnormal pressure.

(4) Jones[21] (1969) defined geopressure "as the zone in which the subsurface fluid pressure significantly exceeds that of the normal hydrostatic pressure of 0.464 psi/ft."

Others use the term "overpressure" to describe a reservoir state having one or more of the above characteristics. Thus, as one can see, various terms, describing an above-normal state of pressure in a reservoir, are employed, and this terminology is rather diverse. In this paper, the terms geopressure, overpressure and abnormal pressure will be used as synonyms to imply a state of unusually high pressure.

Characteristics normally associated with most geopressured reservoirs are:

(1) pressures greater than hydrostatic

(2) abnormally high temperatures

(3) sour or acid gases (H_2S, CO_2)

(4) undercompacted rocks

(5) impermeable seals

(6) high volumes of water

Geopressured reservoirs, because of their unique pressure conditions, have become important targets in the search for hydrocarbons. Many of these geopressured zones were found by chance; the early discoveries often caused more troubles and dangers than they were worth.

A number of measurements have been devised to ascertain the presence or nearness of geopressured zones. Presently, seismic is the only such pre-drilling prediction tool. Certainly a technique to forecast overpressured zones would be invaluable to the oil and gas industry. The only pre-drilling prediction tool, as mentioned above, is the seismic method; all other methods rely upon information while the well is drilling or after the well has been completed. For this reason, it is imperative to examine the predicted seismic responses of geopressured zones in areas where these potentially hazardous zones might exist. The ability to anticipate geopressured zones could save companies millions of dollars and, perhaps, hundreds of lives.

Seismic modeling has become an important exploration method, but has not been thoroughly utilized in interpreting and forecasting reservoirs with abnormally high pressures.

The purpose of this paper is to demonstrate the use and importance of seismic modeling in predicting geopressured zones. The first chapter of this paper is an introduction relating the general significance of geopressured reservoirs to the oil and gas industry. Chapter II deals with the geographic and geologic distributions, origins, trapping mechanisms and seals, and engineering problems associated with geopressured reservoirs. Acoustic parameters and seismic wave theory are discussed in Chapter III. Next, the theory is applied to three different types of overpressured reservoirs, which are described in Chapter IV. These reservoir traps will be digitized; velocities and densities assigned to each layer or formation; reflection coefficients calculated for each boundary between rock layers; and the responses convolved with a 40-Hz, zero-phase Ricker wavelet at a two millisecond sample rate to produce a synthetic seismic section representative of each particular reservoir trap. Variations in reflection coefficient, time thickness, amplitude, frequency, and polarity of the seismic traces will then be studied in order to demonstrate several of the characteristics useful in predicting abnormally pressured reservoirs.

The first model, lenticular sands encased in shales, is a "walk-through" example shown primarily to acquaint the reader with seismic interpretation of reservoir models. The second model involves normally pressured and geopressured channel sands encased in shales and limestones. MODEL C, CASES 1-4 involves a hypothetical case study of a growth-fault reservoir to illustrate how an abnormally pressured reservoir can be anticipated by using polarity, amplitude, frequency and travel-time of the synthetic seismic traces. Even though the solutions, due to vertical and lateral variations in the reservoirs, are not unique, the techniques will illustrate how a potentially hazardous reservoir can be recognized based upon little or no well control. Chapter V deals with "Applications of Reservoir Seismic Modeling" and is followed by a summary, conclusions from this study, and recommendations for future research in Chapter VI.

CHAPTER II

GEOPRESSURED RESERVOIRS

In order to more fully understand the behavior of geopressured reservoirs, it is necessary to examine their geographic and geologic distributions.

Geographic Distribution

Fertl and Timko[15] (1970) listed the following areas of known occurrences of geopressures: (1) NORTH AMERICA (USA: Arkansas, California, Louisiana, Oklahoma, Texas, Wyoming), (2) EUROPE (Austria, Caucasian & Carpathian Regions of Eastern Europe, France, Germany), (3) AFRICA (Algeria), (4) ASIA (FAR EAST: Burma, India, Indonesia, Japan, New Guinea; MIDDLE EAST: Iran, Iraq, Pakistan) and (5) SOUTH AMERICA (Argentina, Columbia, Trinidad, Venezuela). The author wishes to add the following to the above list: (1) NORTH AMERICA (USA: Mississippi, Pennsylvania, New York; CANADA), (2) EUROPE (the Netherlands, North Sea), and (5) ASIA (South China Sea).

Geologic Distribution

Dorfman & Kehle[12] (1974) stated that "geopressured zones are found world-wide in sediments ranging from Cambrian to Pleistocene in age." Among the more familiar abnormally pressured sediments are the Eocene, Oligocene and Miocene sand-shale sequences of the Gulf Coast Province. The most widely publicized geopressured zones in the Mid-Continent are the Morrow-Springer sand-shale sequences of the Anadarko Basin.

The significance of the world-wide distribution, essentially throughout geologic time, of overpressured zones is two-fold: (1) it demonstrates the potential dangers of drilling that might be encountered on any one of the five continents mentioned above, and (2) tends to suggest that the origin of geopressures is non-unique; that is, the existence of all geopressured formations probably cannot be attributed to a single cause.

<u>Origin</u>

Concerning the origins of geopressures, Parker[28] (1973), through field examples, studied the origins of deep Jurassic geopressures in the interior basin of Mississippi and contrasted them with geopressures in the Gulf Coast Tertiary. He concluded:

> Unlike the latter, which result from loading and undercompaction caused by rapid deposition, the Jurassic geopressures are related to geologically late events involving inflation and hydrocarbon phase changes.

Matthews, Rehm, and Louden[26] (1972) discussed the following possible causes of geopressures:

(1) anticlinal structures in oil and gas fields,.

(2) compression (for massive shales) and water expulsion, and

(3) "charging" from deeper zones.

Bradley[8] (1975) indicated that temperature changes "resulting from epeirogenic movements with associated erosion and deposition and long-term changes in climate" appears to be the principal cause of abnormal pressures.

Shephard, Bryant, and Dunlap[32] (1978) found high sedimentation rates and low permeabilities to be the primary causes for the high degree of underconsolidation in Mississippi Delta sediments.

It is not the purpose of this paper to determine the origins of geopressure, and this brief introduction above certainly does not do justice to the subject. For additional information on the topic, Breeze[9] (1970) has an excellent bibliography.

<u>Trapping Mechanisms and Seals</u>

An effective seal is necessary for the generation and maintenance of abnormal pressures. Dickinson[10] (1953) listed three types of seals that are responsible for preserving high pressures: (1) pinchouts, (2) faulting with regional facies changes, and (3) faulting against impermeable rocks.

For any particular zone, absence of an effective seal would cause the overpressures to dissipate, seeking equilibrium. Facies changes and fault traps, even though the most common seals, are not the only ones. Porosity changes (ie., porous to tight facies) in limestones or dolomites may also preserve geopressures. The fluids become trapped and pressured as recharge occurs. Parker[28] (1973) documented that tight carbonates or anhydrites were responsible for sealing geopressures in the Upper Jurassic Smackover-Norphlet section.

In short, an impermeable formation is necessary for confining geopressures. This formation is generally a shale or tight carbonate and the geopressured zone may be trapped by a fault, facies change, or porosity change (or any combination of these).

Engineering Problems

Despite the advantage of usually having hydrocarbon or rare gases associated with geopressured zones, the formations are extremely dangerous upon being penetrated with the drill bit and extreme caution is necessary during drilling operations.

Stuart[35] (1970) lists the following engineering problems which are associated with abnormally high pore-fluid pressures:

(1) blowouts

(2) stuck pipe

(3) lost drilling progress

(4) lost circulation

(5) saltwater flows

First, a blowout is one of the most serious problems facing today's drilling engineer. This disaster, which may result in loss of lives and millions of dollars wasted, occurs when the formation pressure greatly exceeds the mud weight.

Secondly, pipe can become stuck due to sloughing shales or unexpected pressure differentials encountered while drilling. This problem is typical in massive shale sequences (eg., the Atokan or Mississippian shales of the Arkoma Basin). Thirdly, if a well has to be shut down while drilling, there will be loss of time, money, etc. Fourthly, in volcanic areas (eg., N.W. Coast of U.S.), soft clay balls up on the bit and stabilizers to cause lost circulation. If the mud weight is too heavy, it can break down the wall of the hole, become lost in a low pressure formation, and cause lost circulation (McCaslin,[27] 1982). Finally, many of the geopressured zones in the Gulf Coast contain high percentages of saltwater; associated high-pressure flow rates of saline water can cause significant damage to wellsites.

The next chapter will discuss the acoustic parameters which are fundamental to the seismic modeling of overpressured zones.

CHAPTER III

ACOUSTIC PARAMETERS

Velocity and Density

Velocity and density are the two most important rock parameters affecting seismic reflectivity. In this paper, velocity will be used as a general term for compressional elastic wave velocity. Density will be discussed in a later section.

One of the more important basic formulas defining velocity (V) is:

$$V = (E/\rho)^{\frac{1}{2}}, \quad \text{with } E = \text{modulus of elasticity}$$
$$\rho = \text{density}$$

Generally, rocks with higher densities tend to have higher velocities. Equation (1) above suggests that since velocity is inversely proportional to density, velocity should decrease with increasing density (provided E remains constant). This apparent contradiction is solved by noting that an increase in density is accompanied by a corresponding greater increase in the modulus of elasticity.

Among the various factors which influence velocity are porosity, density, fluid saturant, effective pressure, and temperature. Effective pressure is the difference between overburden pressure and fluid pressure. Porosity is, however, the major cause of velocity variation in a sandstone. Hicks and Berry[20] (1956) stated that a porosity change from 3 % to 30 % could cause a 60 % reduction in velocity. Many geopressured zones contain sands with preserved porosities of 30-35 %. Velocity alone, then, is not diagnostic of rock types because of the range (overlap) of velocities. However, within a given area or geologic province, the velocities of sands and shales are fairly uniform under similar conditions of temperature and pressure and do not show such a wide range as mentioned above. Generally, limestones have high velocities (19,000-21,000 fps), followed by sandstones (1,000-17,500 fps), and then shales (1,000-15,500 fps). These ranges for limestones, sandstones and shales are the maximum ranges (or end members) that have been observed for each lithology on a world-wide basis. Within a particular basin or geologic province, one would observe a much smaller range in velocities, perhaps on the order of 2000-3000 feet per second, and usually less than 1000 feet per second, for each rock type. However, velocity is not the only acoustic parameter which must be considered in seismic modeling.

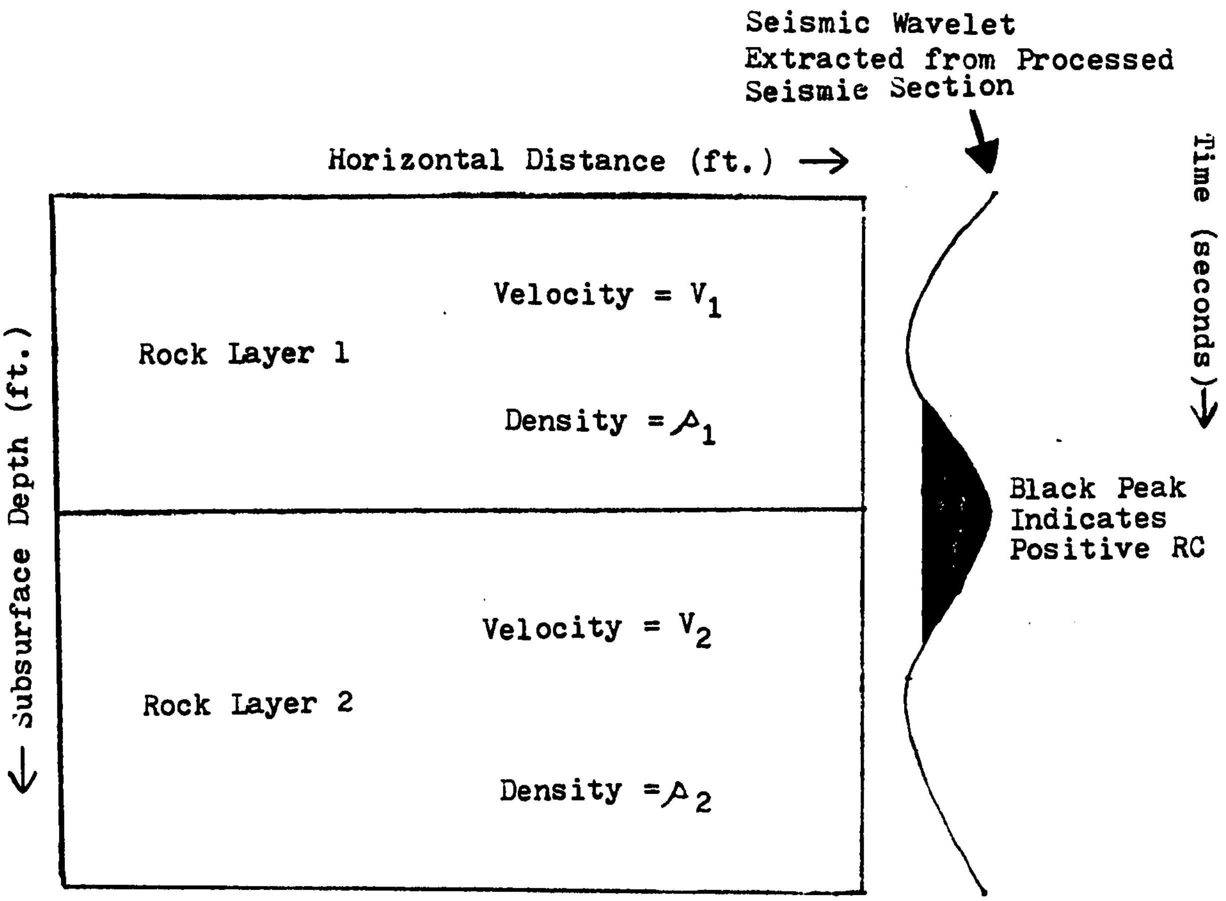
Density, on the other hand, will be used as a general term describing the mass per unit volume (in gms/cc) of the rocks and fluid saturants in CHAPTER IV.

Even though density is important in determining acoustic impedance (A.I. = Velocity x Density), it does not play as large a role as velocity since variations in density are generally small compared to velocity variations (there will be noted exceptions to this statement in CHAPTER IV).

The overall rock density is primarily determined by its porosity and type of fluid saturant (oil, gas, water, etc.). Generally, gas-saturated sandstones tend to be less dense than water-filled sandstones, which are less dense than tight sands. Furthermore, in the Mid-Continent, 2.65 gms/cc is normally assigned to sandstones, 2.55 gms/cc to shales, and 2.71 gms/cc to limestones.

Acoustic Impedance

Velocity and density dictate the behavior of most seismic reflections. Acoustic impedance is defined as "the seismic velocity multiplied by density" (Sheriff,[34] 1976). Consider the two rock media in Figure 1, each having a characteristic velocity and density. These symbols for velocity and density will be utilized throughout this paper. The acoustic impedance of layer 1 = $(AI)_1 = V_1\rho_1$, and the acoustic impedance of layer 2 = $(AI)_2 = V_2\rho_2$.



Acoustic impedance (layer 1) = $V_1\rho_1$.

Acoustic impedance (layer 2) = $V_2\rho_2$.

$$\text{Reflection Coefficient} = RC = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1}$$

Figure 1. Acoustic Impedance and Reflection Coefficient for Two Rock Layers with $V_2\rho_2 > V_1\rho_1$.

Reflection Coefficient

The reflection coefficient, RC, for the above case, at the interface between layers 1 and 2 (Figure 1), is:

$$RC = \frac{(AI)_2 - (AI)_1}{(AI)_2 + (AI)_1} = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1} .$$

The reflection coefficient can be positive or negative. The convention to be used here is: a positive reflection coefficient implies going from a lower acoustic impedance formation to a higher acoustic impedance formation and generates a black peak to the right on the synthetic seismic section (Figure 1). Conversely, a negative reflection coefficient implies that the seismic wave travels from a higher acoustic impedance formation to a lower acoustic impedance formation ($V_1\rho_1 > V_2\rho_2$) and generates a trough to the left on the seismic section. Generally, good reflections are those with reflection coefficients >0.15 and <-0.15. Of course, a reflection coefficient equal to zero implies that there is no reflection generated.

The acoustic impedance contrasts and the resulting reflection coefficients will be the basis for much of the interpretation in following chapters; thus, it is important that one understands these basic concepts. The following chapter describes three distinct types of geopressured reservoir traps and the synthetic seismic models for each trap. However, before examining the models, it is necessary to provide the necessary framework within which to examine the models. The next section will discuss several of the constraints of 2-D Seismic Modeling, thus providing the necessary framework.

LIMITATIONS OF 2-D SEISMIC MODELING

Several of the constraints encountered in the seismic simulation of geopressured reservoirs are as follows:

(1) Dimensionality: All models were two-dimensional rather than three-dimensional. Three-dimensional modeling is tremendously expensive, primarily because of computer time requirements, and three-dimensional seismic acquisition and processing is usually greater than ten times more expensive than comparable two-dimensional acquisition and processing.

(2) Raypath: The models assume normal incidence raypaths: this is a good assumption since most seismic reflections are within $\pm$ 10-15° of normal incidence.

(3) Frequency: A 40-Hz Ricker wavelet was used, rather than, for example, 80-Hz. Again, this is a good assumption since most seismic data has a dominant frequency content at approximately 40-Hz.

(4) Sample Rate: Generally, the models employed a 2 millisecond sample rate. One millisecond could have been used for perhaps better resolution, but was determined to be more costly and most seismic data is recorded and processed with a 2 millisecond or a 4 millisecond sample rate.

(5) Uniqueness: Strictly speaking, the solutions presented are non-unique; however, they are reasonable estimates given the local geological structure and stratigraphy. The best usage of these models would be in development-type endeavors which have adequate well control to document the structure and stratigraphy. These models are useful in exploratory work, but the interpreter must be aware of the limitations. Because of the very large changes in velocities and densities of geopressured zones, modifying the velocities and densities in the models by 500-1000 feet per second and 0.1-0.2 grams per cubic centimeter generally does not change the seismic responses appreciably, according to the author's mathematical calculations.

CHAPTER IV

RESERVOIR MODELS

In attempting to model the seismic signature of a reservoir, the engineer is faced with the immediate problem of determining the proper rock and fluid parameters which satisfy the laws governing the behavior of the reservoir. The important parameters to be considered in such a seismic model are: (1) velocity, (2) density, (3) lithology, (4) porosity, (5) rock thickness, and (6) fluid saturant.

Some of the above are dependent variables (eg. velocity and fluid saturant are interrelated), and all are important in determining the acoustic impedance contrasts necessary to generate a seismic signature characteristic of a particular geopressured zone or normally pressured sequence. Other parameters such as pressure, temperature, etc. cannot be directly input into the model, but influence the values of the input variables and must be kept in mind.

A flow diagram for seismic modeling is shown in Figure 2. The first step involves a geologic model which contains an accurate description of the structure (geometry) and stratigraphy of the reservoir and its surroundings. Lithologies, thicknesses, facies changes, pressure conditions, porosities, and fluid saturants are all part of the geologic model.

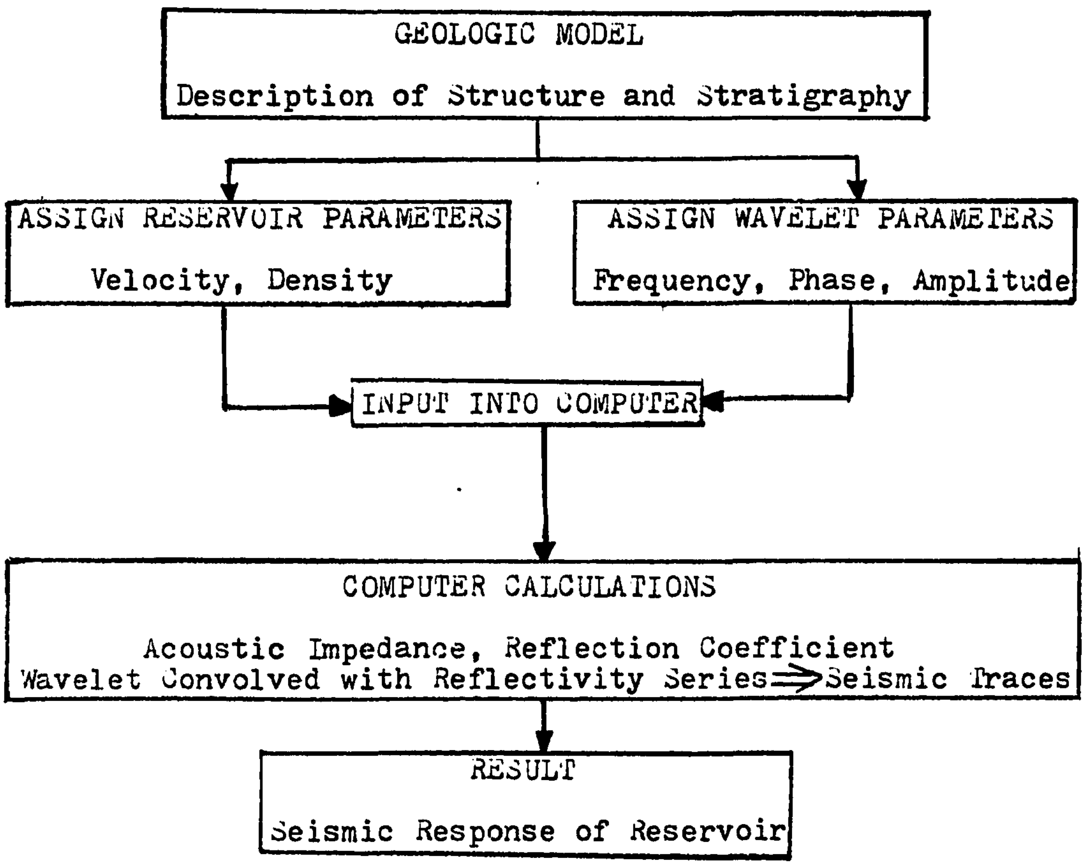


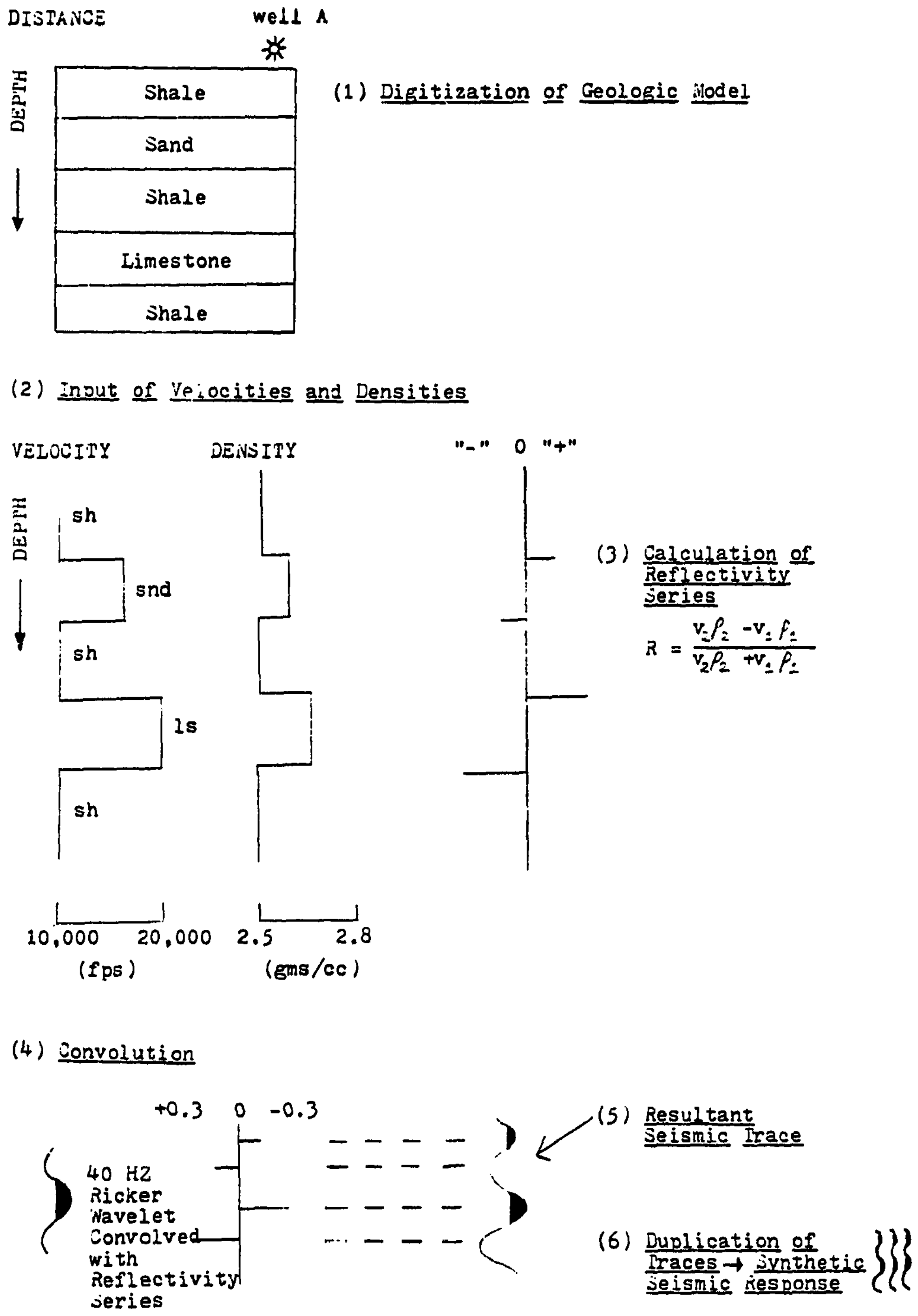
Figure 2. Seismic Modeling: Flow Diagram

Next, reservoir parameters and seismic wavelet parameters are assigned. The two major reservoir variables in this study are velocity and density. The effect of fluid saturants such as gas and water are taken into account by the velocity and density terms. The velocities and densities used in this paper are reasonable estimates and are based upon the author's engineering judgment, experience and seismic expertise in geopressured zones, as well as upon published reports in the literature. As far as wavelet parameters are concerned, a 40-Hz, zero-phase Ricker wavelet was convolved with the reflectivity series, sampled at two milliseconds, to generate the seismic models. The frequency of 40 Hz was used since it is a typical dominant frequency for most seismic reflection work. The amplitude factor of 1.0, a scaling factor based upon true relative amplitudes, was used for all models except for MODEL B, CASE 2, where 0.50 was employed.

After reservoir and wavelet parameters have been assigned to the geologic model, the simulated reservoir is digitized and input to the computer, which calculates the acoustic impedance and the resulting reflection coefficients at each of the model's interfaces. Next, the 40-Hz Ricker wavelet is convolved with the reflectivity series, and the amplitude is scaled to produce seismic traces: the result is the synthetic seismic response of the reservoir, displayed as a time section. The above process is actually called direct or forward 2-D (two-dimensional) modeling. This is in contrast to inverse modeling, which starts with the seismic trace and works backward toward finding a matching geologic model. Figure 3 demonstrates the detailed methodology for constructing two-dimensional seismic models. After the model is made, it is interpreted based upon phase, polarity, amplitude, frequency, etc.

Oklahoma Seismic Corporation's two-dimensional seismic modeling programs were utilized to construct the models in this study. Their computer facilities that were used include a PRIME 400 and TEKTRONICS 4014-1 with a combination SUMMA-GRAPHICS MODEL ID-2 OTR-4260 and HAMILTON VR-20 digitizer, and a COMPLOT DP-8 plotter.

Figure 3. METHODOLOGY FOR TWO-DIMENSIONAL SEISMIC MODELS



MODEL A, CASE 1

The purpose of this model is two-fold: (1) to acquaint the reader with seismic interpretation of reservoir models by providing a "walk-through" example and (2) to study the modeled responses of abnormally pressured versus normally pressured lenticular sands encased in shales.

Geologic Setting

Figure 4 shows three typical overpressured Oligocene Gulf-Coast lenticular sands, ranging from 0-60 feet thick, encased in a massive shale sequence. On the left-hand side of the figure, depth (in feet) is plotted. At the top, distance (1000 feet) and the shotpoint number (assuming dynamite to be the source of the real seismic data) are annotated.

Reservoir Acoustic Parameters

At the extreme top of Figure 4 is a table describing the event (or rock unit) along with its velocity (in feet per second) and density (in grams per cubic centimeter = gms/cc). For example, event 0, which represents the shale above the uppermost geopressured sand, has a velocity of 7500 feet per second and a density of 2.60 gms/cc., while the uppermost geopressured sand (event 1) has a velocity of 4500 feet per second and density of 2.20 gms/cc.

The following values of velocity and density were

EVENT	VELOCITY	DENSITY
0	7500	2.60
1	4500	2.20
2	7500	2.60
3	4500	2.20
4	7500	2.60
5	4500	2.20
6	7500	2.60

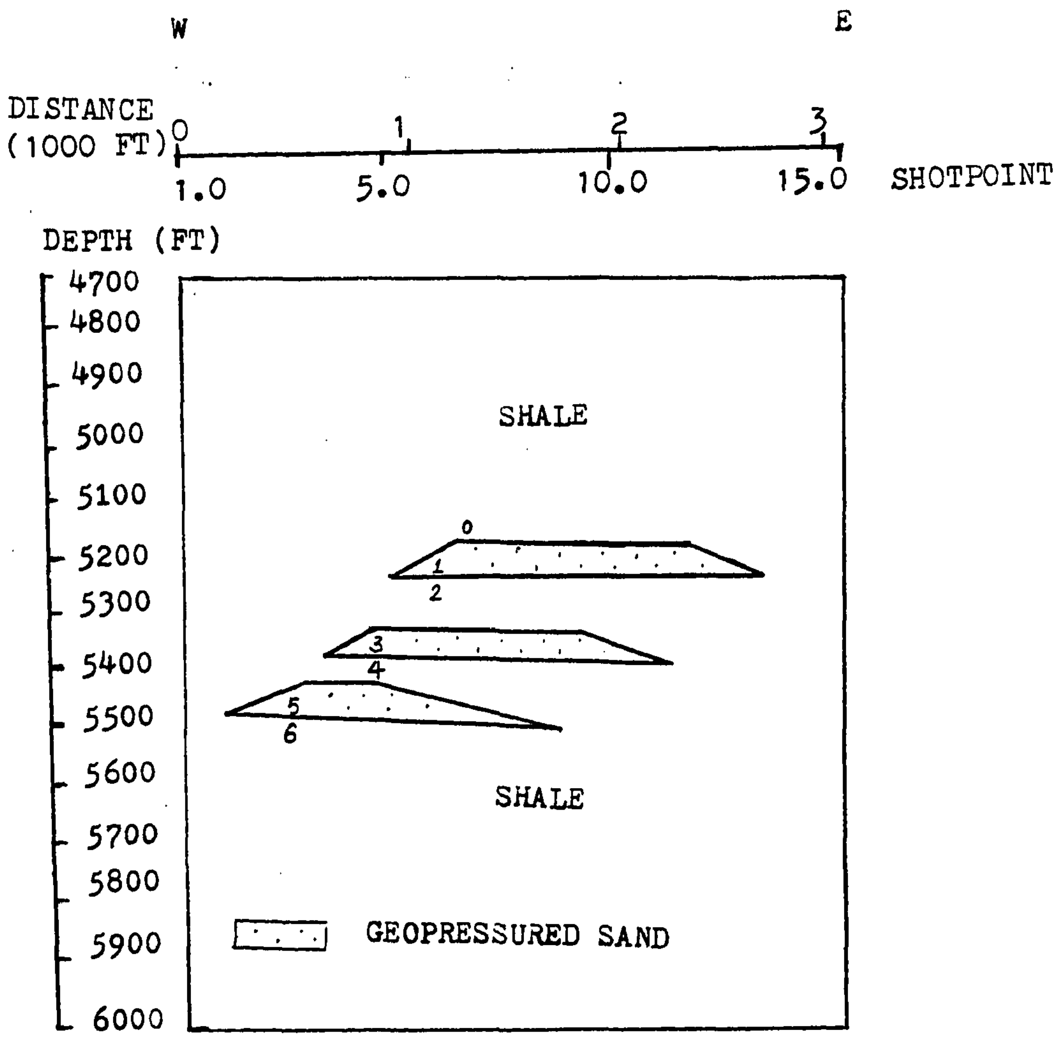


Figure 4 . Oligocene Reservoir (Geopressured Lenticular Sands)

assumed for MODEL A, CASE 1:

Lithology	Velocity(fps)	Density(gms/cc)
Shale	7500	2.6
Sand (geopressured)	4500	2.2

A geologic model using the above acoustic parameters was then digitized and acoustic impedances and the resulting reflection coefficients were calculated. Again, the uppermost shale in Figure 4 has an acoustic impedance (abbreviated AI) equal to 7,500 fps x 2.6 gms/cc, while the geopressured sand has an AI equal to 4,500 fps x 2.2 gms/cc. The reflection coefficient (abbreviated RC) at the boundary between the shale (event 0) and the sand (event 1) is:

$$RC = \frac{4500(2.2) - 7500(2.6)}{4500(2.2) + 7500(2.6)} = -0.326 \quad \text{(Table 1)} \quad .$$

Note that RC is a dimensionless number and that it is negative (this means the sand has a lower acoustic impedance than the shale and is consistent with the convention established in Chapter III).

Reflection coefficients are then generated at each of the interfaces, sampled every two milliseconds in time, and then are convolved (filtered) with the 40-Hz Ricker wavelet to produce a synthetic seismic section.

Reservoir Model

Figure 5 is a two-dimensional model of three abnormally pressured lenticular sands encased in shales.

W E

FILTER TYPE : RICKER
PHASE : ZERO
POLARITY : POSITIVE

FREQUENCIES : 40 HZ

SAMPLING RATE (MS) : 2
AMPLITUDE FACTOR : 1.00
SHOTPOINT INTERVAL (FT.) : 220

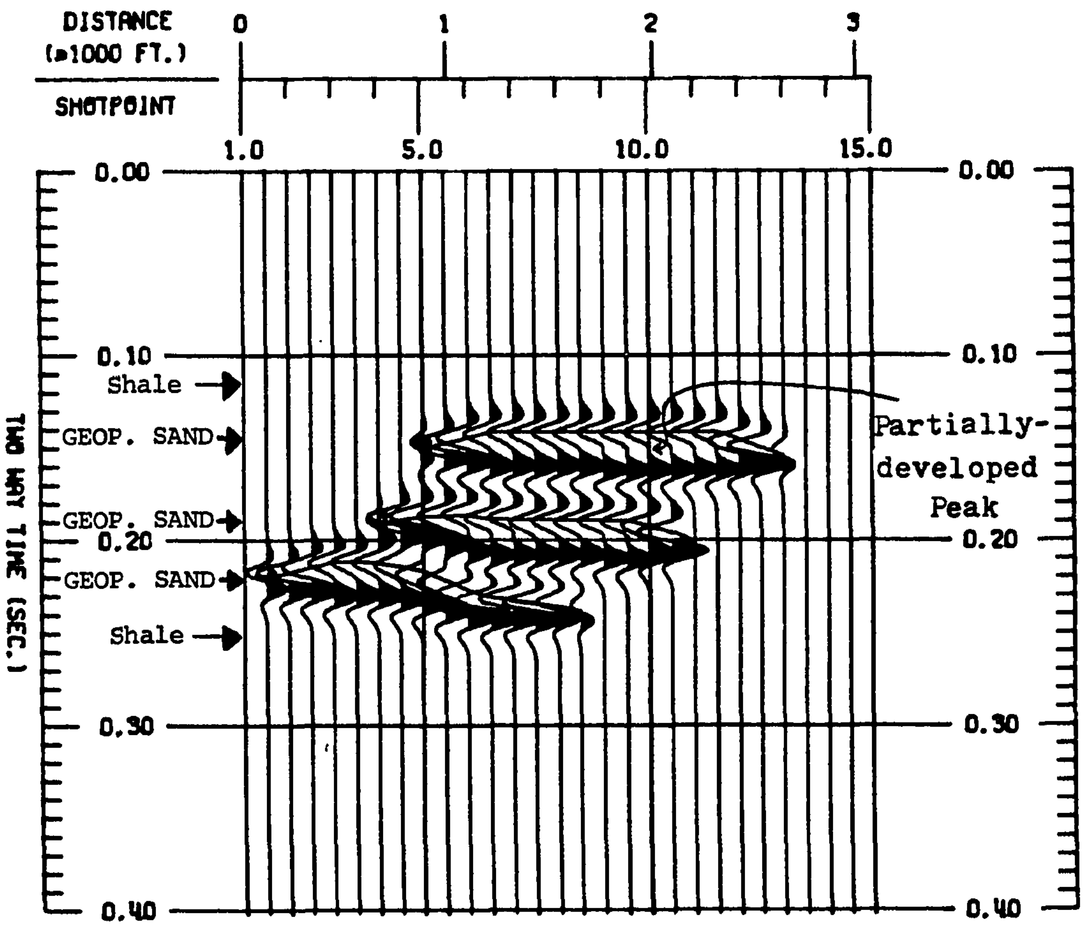


Figure 5. Seismic MODEL A: CASE 1; Oligocene Reservoir (Geopressured Lenticular Sands)

On the left and right-hand sides of Figure 5 is the two-way travel-time (in seconds) of the seismic wave and is referenced to an arbitrary datum. Horizontal distance along the ground (1000 feet) is plotted at the top, along with the corresponding shotpoint annotation (with each shotpoint 220 feet apart). A 40-Hz, zero-phase, positive polarity Ricker wavelet was convolved with the reflectivity series, sampled at two milliseconds, the amplitudes were scaled, using a factor of 1.00, and then the resulting seismic traces were displayed in the form of a synthetic seismic section corresponding to the response of the geopressured sands and shales. An overlay of the digitized model is plotted on the synthetic seismic section using thin black lines for ease of interpretation.

Now that the model has been obtained, how does one interpret it? The obvious characteristics to examine are reflection coefficient, amplitude, frequency, polarity, travel-time thickness and waveform changes. Some or most of these may be important in the interpretation of a particular model.

First, note that the seismic model (Figure 5) defines the geometry of the individual sands; that is, the sands appear lenticular in shape, tapering horizontally at each end. These sands are said to be totally resolved, which means the top of the sand corresponds to a peak and the bottom corresponds to a peak and the time separation (milliseconds) can be measured. In other words, the seismic model shows essentially a one-to-one correspondence with the digitized geologic model.

Secondly, note the extremely high amplitudes that are present at the bases of each geopressured sand. These high amplitude events, which are due to large acoustic impedance contrasts and are typical of some sand-shale sequences in the Gulf Coast, are termed "bright spots." Table 1 is the series of reflection coefficients generated at the tops and bottoms of the overpressured sands. An important point to be made is: Table 1 demonstrates that the reflection coefficients are equal, though reversed in polarity, for the top and bottom of each sand. Since normal polarity was used, the base (going from low to high acoustic impedance) appears as a bright spot because of the black peak. In reality, the top and bottom of each overpressured sand is equally "bright," depending upon the polarity used. Thus far, time thickness (relating to reservoir resolution), reflection coefficient, polarity and amplitude (relating to bright spot indicators) have been discussed. Another parameter to be considered is frequency. The 40-Hz Ricker wavelet was able to resolve the top and bottom of each sand. This is not always the case and depends upon unit thickness, noise, etc. The Ricker wavelet is one in which the attentuation is proportional to the

TABLE 1

Reflection Coefficients: MODEL A, CASE 1

Horizon	Reflection Coefficients	Lithologic Top
1	-0.326	Top Sand
2	0.326	Base Sand
3	-0.326	Top Sand
4	0.326	Base Sand
5	-0.326	Top Sand
6	0.326	Base Sand

square of the frequency. MODEL B, CASE 2 will demonstrate a situation in which very thin channel sands are not resolved by peaks and troughs. Finally, waveform character changes should be considered. Shotpoint 10, at 0.15 seconds, denoted by the arrow in Figure 5, illustrates a slight peak (that is, not fully developed) that "tries to come in." This phenomenon is called a tuning effect. The wavelength and thickness of the sand are such that time separation is almost apparent. Furthermore, tuning thickness is generally considered to be approximately equal to $\frac{1}{4}\lambda$, where λ = the dominant wavelength. For this example,

$V = f\lambda$, where

V = velocity (fps)
f = frequency (cps)
λ = wavelength (ft)

and thus,

$$4500 = 40\ (\lambda),\ \text{so that}$$

$$= 112.5\ \text{feet};$$

$$\frac{1}{4}\lambda = 28.13\ \text{feet.}$$

This implies that a bed must be at least 28.13 feet thick before it is resolved by peak and trough separation.

Notice that the two uppermost sands in this example exhibit this tuning phenomenon by containing an extra "leg" or peak within each sand unit.

In summary, this walk-through example has shown (1) how to model a reservoir and (2) the parameters or characteristics (seismic attributes) which are important in understanding the synthetic seismic responses of the model. Variations in time thickness, amplitude, polarity, frequency, and overall waveform character are important attributes in interpreting the model.

MODEL A, CASE 2

Geologic Setting

CASE 2 represents three discrete normally pressured tight sands (same thicknesses and geometries as in CASE 1) encased in shales (Figure 6).

Reservoir Acoustic Parameters

The following velocities and densities will be used in MODEL A, CASE 2:

Lithology	Velocity(fps)	Density(gms/cc)
Shale	7500	2.60
Sand (Normally pressured)	10000	2.65

Velocities of the shales in CASES 1 and 2 are the same; however, the geopressured sands in CASE 1 have much slower velocities and lower densities than the shales in which they are encased. CASE 2 contains normally pressured sands in which the opposite is true: here the sands have higher velocities and densities than the shales.

An amplitude scaling factor of 0.50, instead of the usual 1.0, was employed for better resolution.

Reservoir Model

Figure 7 is a two-dimensional model of three normally pressured lenticular sands encased in shales. The tops of the tight sands appear as peaks and the bottoms appear as troughs; this is in contrast to troughs and peaks (just

EVENT	VELOCITY	DENSITY
0	7500	2.60
1	10000	2.65
2	7500	2.60
3	10000	2.65
4	7500	2.60
5	10000	2.65
6	7500	2.60

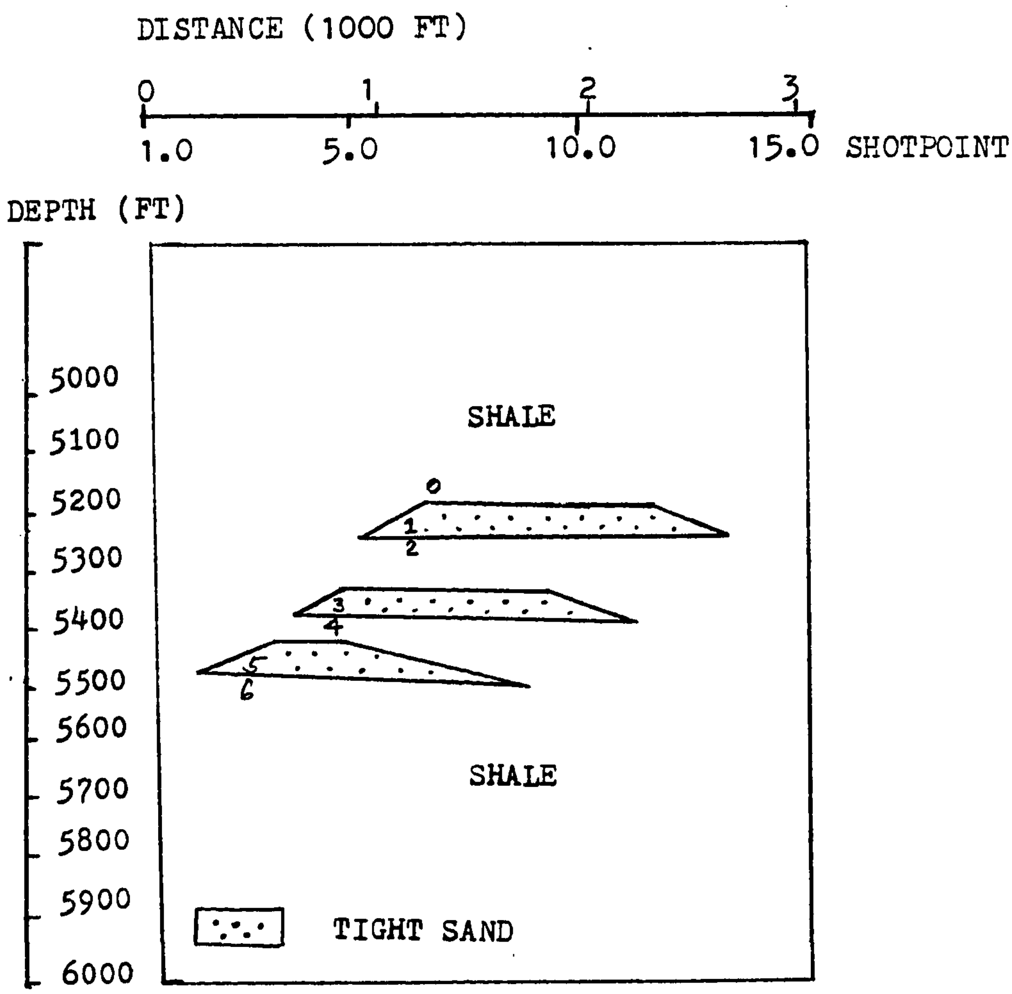


Figure 6. Oligocene Reservoir (Normally Pressured Lenticular Tight Sands)

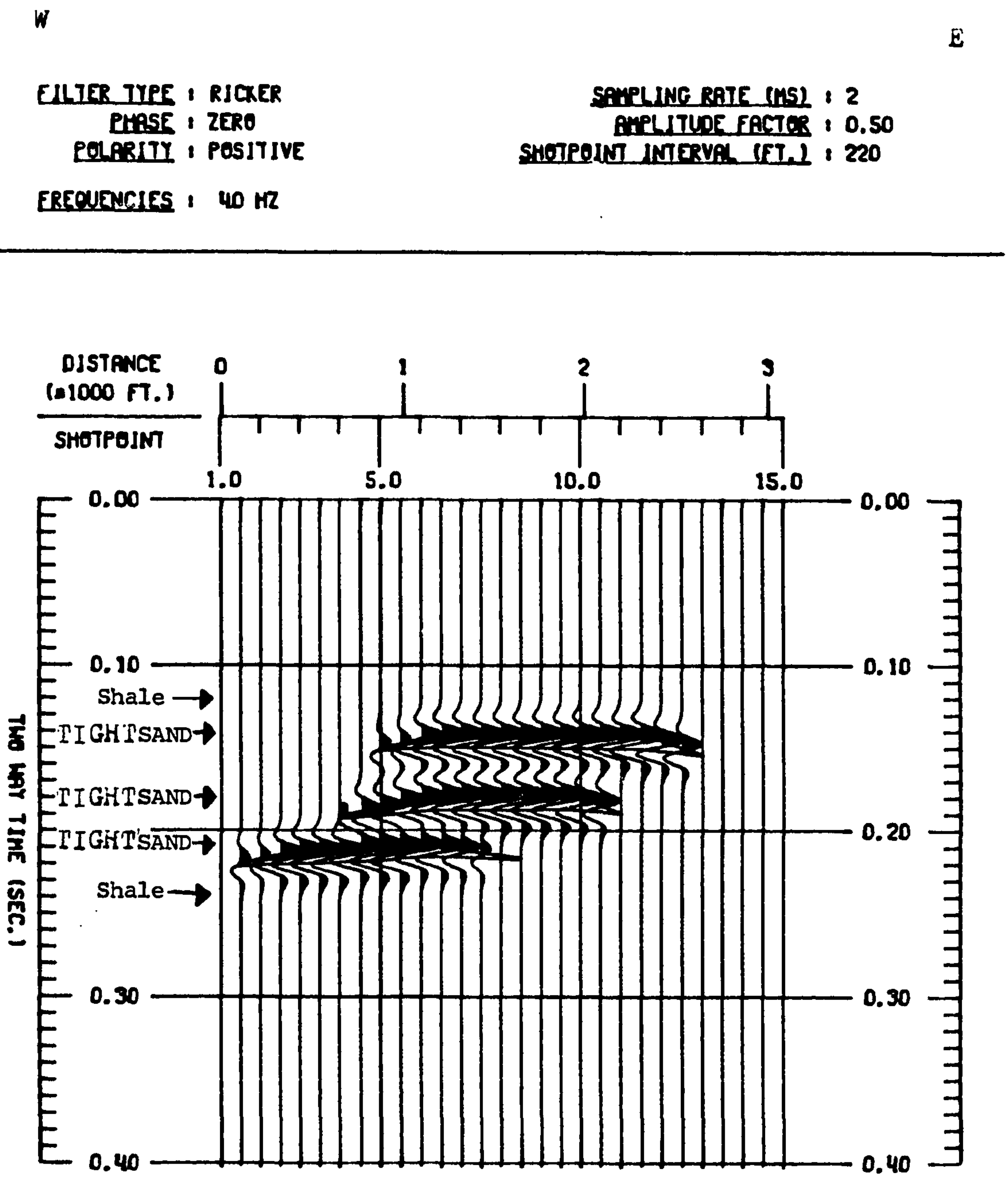


Figure 7. Seismic MODEL A: CASE 2; Oligocene Reservoir (Normally Pressured Tight Sands)

the opposite), respectively, in the previous case of geopressured sands. As in CASE 1, the sands are totally resolved. Also, the lowermost sand shows a distinct velocity pullup compared to its geopressured counterpart in CASE 1. The converse could also be stated. Table 2 lists the reflection coefficients for this case. Note that the absolute values of the reflection coefficients in the case of normally pressured sands encased in shales are approximately one-half (0.152 compared to 0.326) those of the geopressured sands in CASE 1.

Discussion

MODEL A, CASE 2 points out one of the pitfalls associated with "bright-spot" analysis and consequent drilling based upon "bright-spot" analysis. The three high amplitude events ("bright-spots") in this case are not due to the presence of hydrocarbons at all but rather to the strong acoustic impedance contrasts between tight sands and shales. A major clue that these are not gas sands, perhaps, is the fact that there is no apparent velocity sag (which is usually associated with thick gas sands encased in shales); instead, the high amplitude peaks associated with the tops of the tight sands, show distinct convex curvatures due to the high velocity material encased in the shales. It should also be mentioned that even though the shale separating the two uppermost sands is approximately the same thickness

TABLE 2

Reflection Coefficients: MODEL A, CASE 2

Horizon	Reflection Coefficient	Lithologic Top
1	0.152	Top Sand
2	-0.152	Base Sand
3	0.152	Top Sand
4	-0.152	Base Sand
5	0.152	Top Sand
6	-0.152	Base Sand

(Figure 6) of the uppermost sand, the time thickness of each sand is considerably less, due to the higher sand velocities. A tuning phenomenon, analogous to CASE 1, can also be noted at shotpoint 5 corresponding to 0.20 seconds. As the thickness between the middle sand and lower sand decreases to a critical value, the peak at 0.20 seconds "fades out."

The above model, CASES 1 and 2, has, hopefully, served two functions: (1) acquainted the reader with how to set up a seismic model of a reservoir and how to interpret the model, and (2) given the reader several seismic attributes to examine that could be beneficial in distinguishing between geopressured versus normally-pressured lenticular sands typical of the Gulf Coast.

MODEL B, CASE 1

Geologic Setting

The next model to be discussed is a typical Pennsylvanian (Mid-Continent) channel sand sequence encased in shales and limestones. This model is analogous to the Lower Atokan sequence of the Arkoma Basin or the Morrow-Springer section of the Anadarko Basin. CASE 1 contains two geopressured channel sands, approximately 1400 feet in lateral extent: the uppermost being a geopressured 65-feet thick gas sand and the lowermost being a 40-feet thick geopressured water sand (Figure 8). The interval from 12,630 to approximately 12,900 feet is overpressured.

Reservoir Acoustic Parameters

Table 3 is a list of the parameters used in MODEL B, CASE 1.

Reservoir Model

Figure 9 is a two-dimensional model of two abnormally pressured channel sands encased in shales and limestones. Sand geometry is reflected by the synthetic section. Note the apparent "downcutting" of the channel sands into the underlying shales. Both sands are resolved in terms of peak and trough separation.

Discussion

Table 4 is the reflectivity series for MODEL B, CASE 1.

Figure 8. Pennsylvanian Reservoir
(Geopressured Channel Sands)

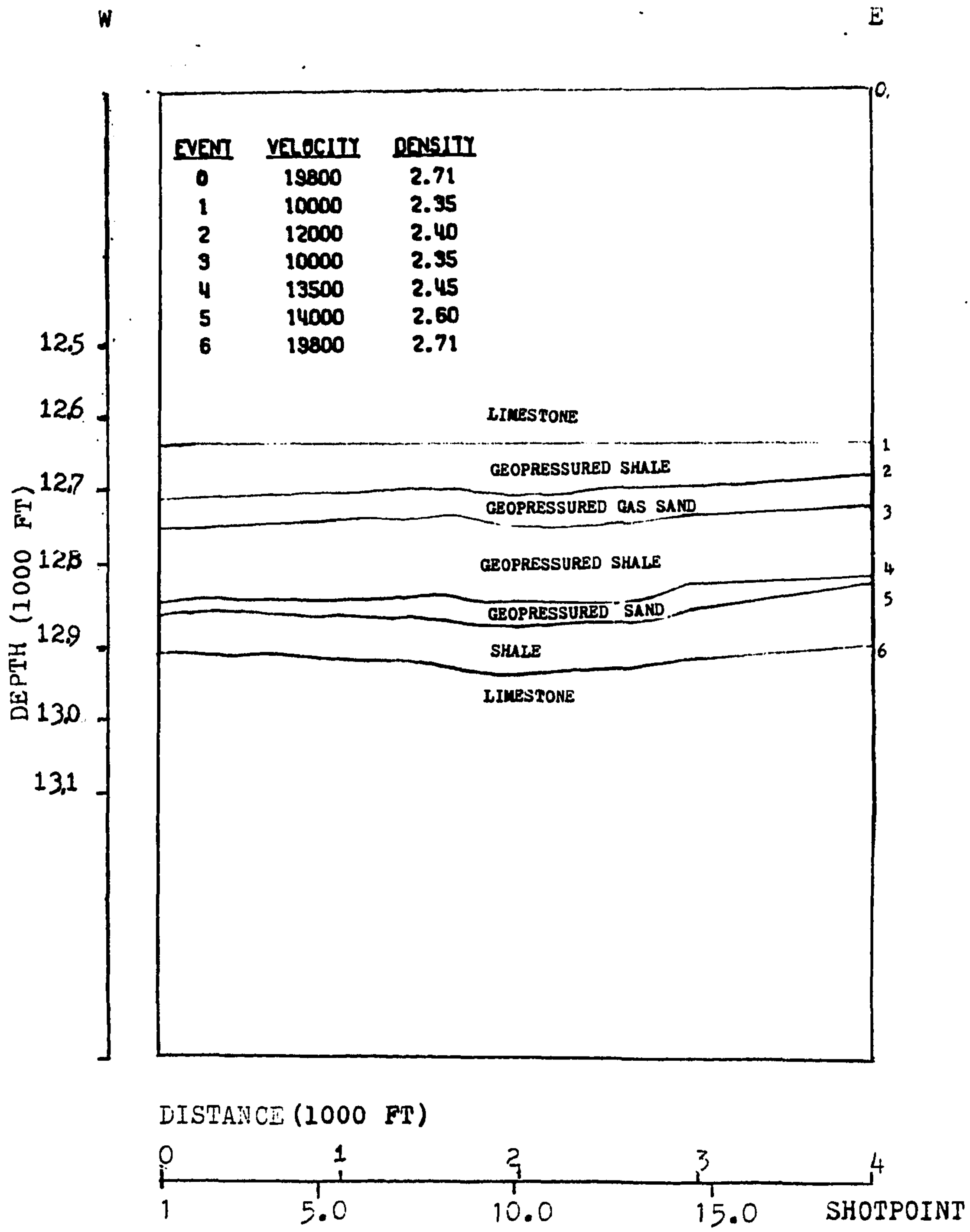


TABLE 3

Acoustic Parameters: MODEL B, CASE 1

Lithology	Velocity(fps)	Density(gms/cc)
limestone	19800	2.71
shale	13500	2.60
shale (geopressured)	10000	2.35
sand (geopressured water)	13500	2.45
sand (geopressured gas)	12000	2.40

W FILTER TYPE : RICKER SAMPLING RATE (MS) : 1 E

PHASE : ZERO AMPLITUDE FACTOR : 1.00

POLARITY : POSITIVE SHOTPOINT INTERVAL (FT.) : 220

FREQUENCIES : 40 HZ

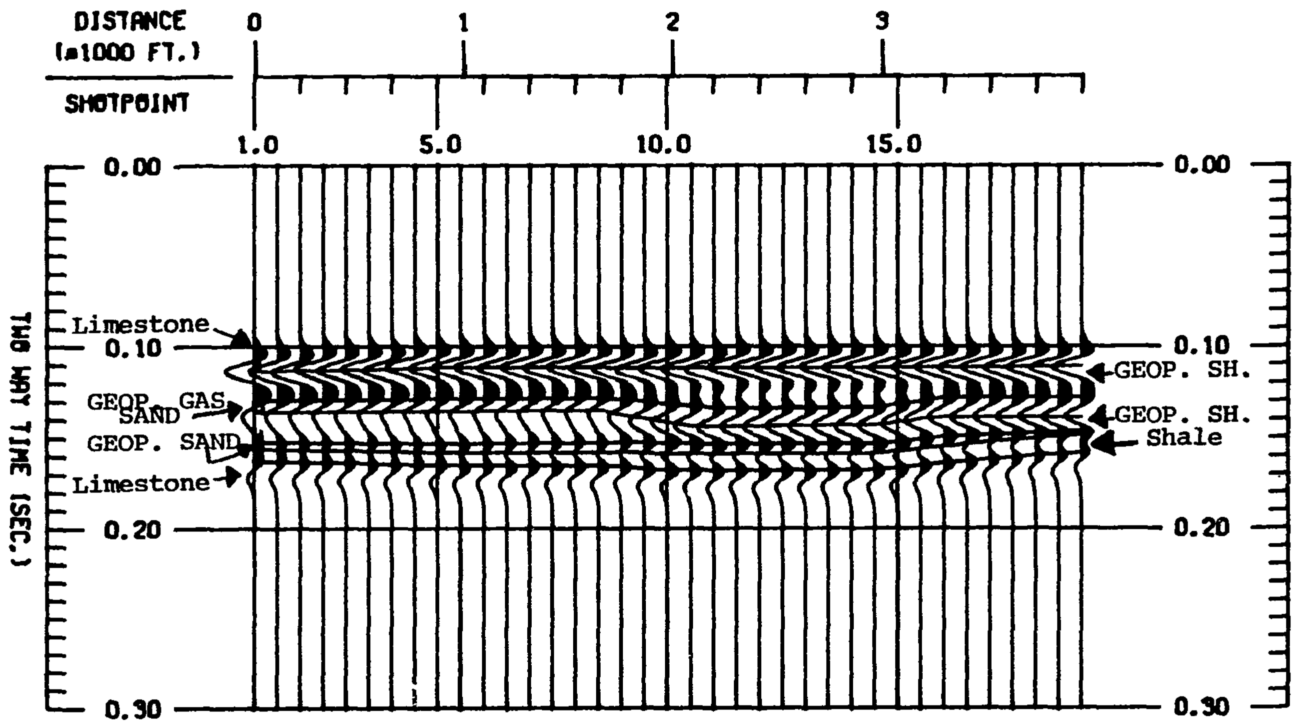


Figure 9. Seismic MODEL B: CASE 1; Pennsylvanian Reservoir (Geopressured Channel Sands)

TABLE 4

Reflection Coefficients: MODEL B, CASE 1

Horizon	Reflection Coefficient	Lithologic Top
1	-0.391	Geopressured Shale
2	0.101	Geopressured Gas Sand
3	-0.101	Geopressured Shale
4	0.169	Geopressured Sand
5	-0.048	Shale
6	0.192	Limestone

Reflection coefficients range from -0.391 to 0.192. From shotpoints 10-15, at the top of the geopressured gas sand (0.13 sec) is a character change known as a doublet ( ). It is formed where the geopressured gas sand channel downcuts into the underlying shale, and is definitive in delineating the shape and lateral extent of the underlying channel sands (Figure 9).

MODEL B, CASE 2

Geologic Setting

MODEL B, CASE 2 is the same in terms of unit thicknesses and geometries as in CASE 1, except that all the geopressured zones have become normally pressured (Figure 10).

Reservoir Acoustic Parameters

Table 5 is a list of velocities and densities used in CASE 2, while Table 6 summarizes the reflection coefficients.

Reservoir Model

Figure 11 is a two-dimensional model of two channel sands, the uppermost being gas productive and the lowermost being tight; both sands are encased in shales and limestones. Overall, sand geometry, as in CASE 1, is reflected by the apparent "downcutting" of the channel sands. Contrary to CASE 1, neither of these sands is resolved by peak and trough separation.

Discussion

Reflection coefficients range from -0.209 to 0.192. The thinness of the sands coupled with the relatively low reflection coefficients illustrate why the channel sands are not resolved by peaks and troughs. The two major differences between CASES 1 and 2 are: (1) reflection strength: the top of the uppermost geopressured gas sand in CASE 1 is much stronger than the top of the gas sand in CASE 2 and the top of the basal limestone in CASE 2 has a higher amplitude than the previous case, and (2) the channel sands in CASE 2

Figure 10. Pennsylvanian Reservoir (Normally Pressured Channel Sands)

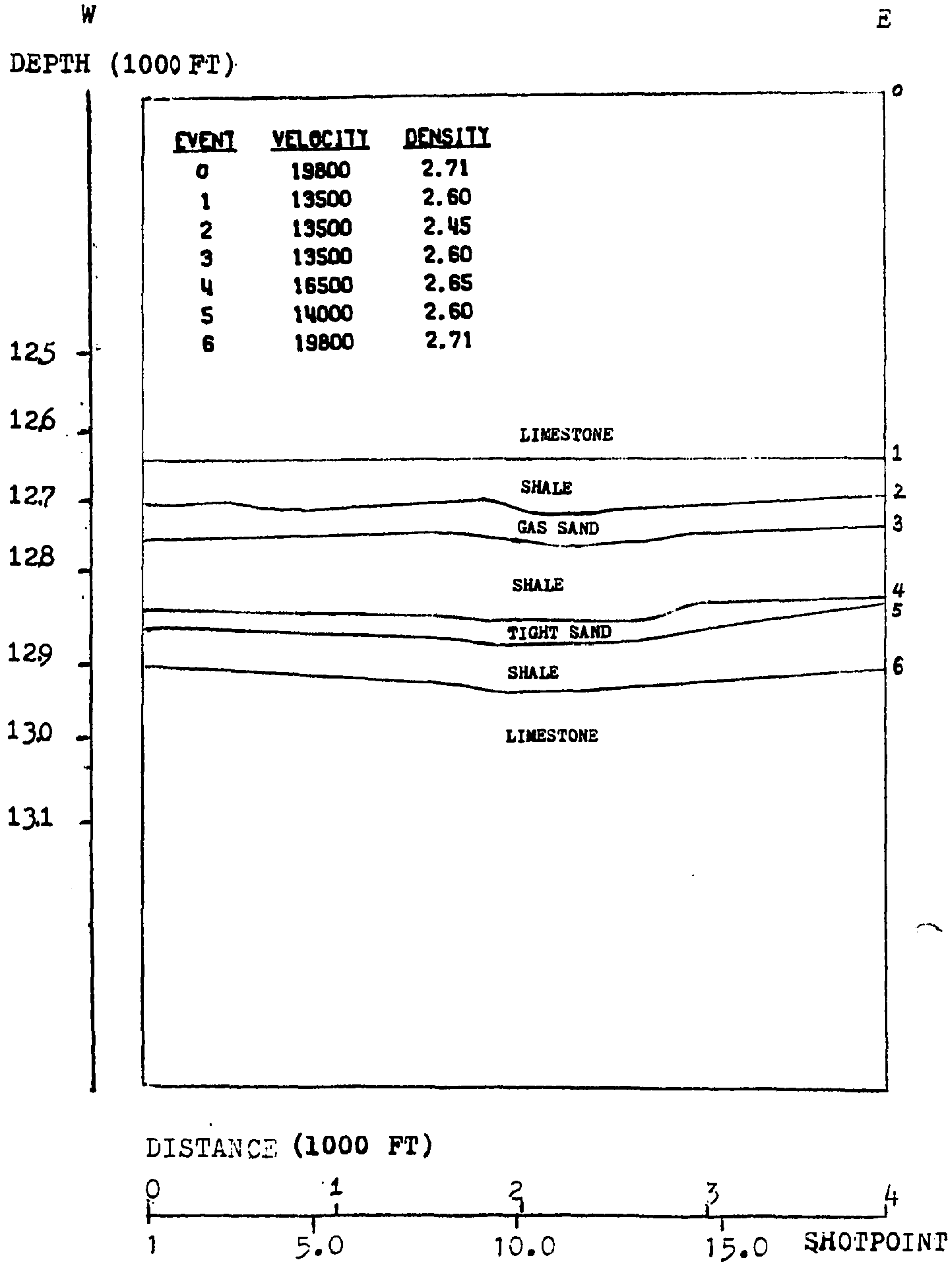


TABLE 5

Acoustic Parameters: MODEL B, CASE 2

Lithology	Velocity(fps)	Density(gms/cc)
limestone	19800	2.71
shale	13500	2.60
sand (gas)	14000	2.60
sand (tight)	16500	2.65

TABLE 6

Reflection Coefficients: MODEL B, CASE 2

Horizon	Reflection Coefficients	Lithologic Top
1	-0.209	Shale
2	0.000	Gas Sand
3	-0.000	Shale
4	0.109	Tight Sand
5	-0.091	Shale
6	0.192	Limestone

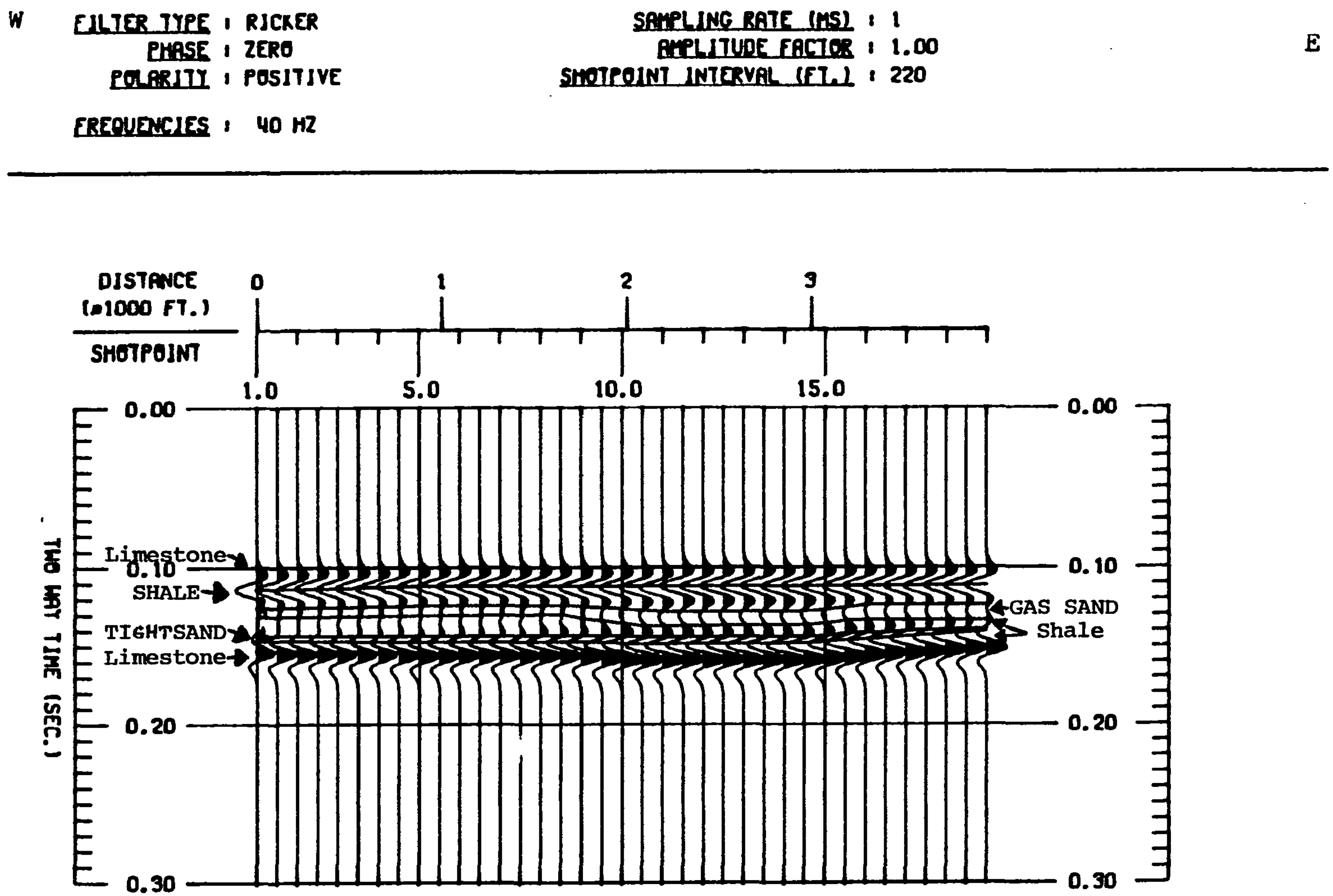


Figure 11. Seismic MODEL B: CASE 2; Pennsylvanian Reservoir (Normally Pressured Channel Sands)

are not totally resolved as in CASE 1. The importance of this model is that differences in reflection strength and seismic character exist between abnormally pressured versus normally pressured channel sands encased in shales; these differences can be detected and might aid in detecting over-pressured reservoirs.

MODEL C, CASE 1 (CASE STUDY)

The next model, a typical Miocene (Gulf Coast Province) growth fault reservoir with interbedded sands and shales, is a hypothetical case study which will conclusively demonstrate the importance and applications of seismic modeling in predicting geopressured reservoirs.

Company A, a fairly large independent operator in the Gulf Coast, had substantial acreage holdings which were near expiration. The large block of acreage was immediately south of two producing wells, B and C, which had cumulative productions of 15 billion cubic feet of gas over a three-year period (Figure 12). The field was also fault-bounded on the east and well A, drilled downthrown to the fault three years previously, by Company B, encountered an unexpected thin geopressured shale and sand, blew out, and killed five people. The location was abandoned and never re-drilled. With this exception, no geopressured zones had been encountered within a 15-mile radius.

Company A was apprehensive about drilling downthrown because of the blowout accident mentioned above; drilling costs were beginning to escalate and if a thick geopressured sequence were encountered, the extra mud weight required to control the well would add to the expense. Of course, the inherent risk of perhaps finding no hydrocarbons was an additional concern. However, most of the company's acreage holdings were downthrown and if a thick, overpressured, gas

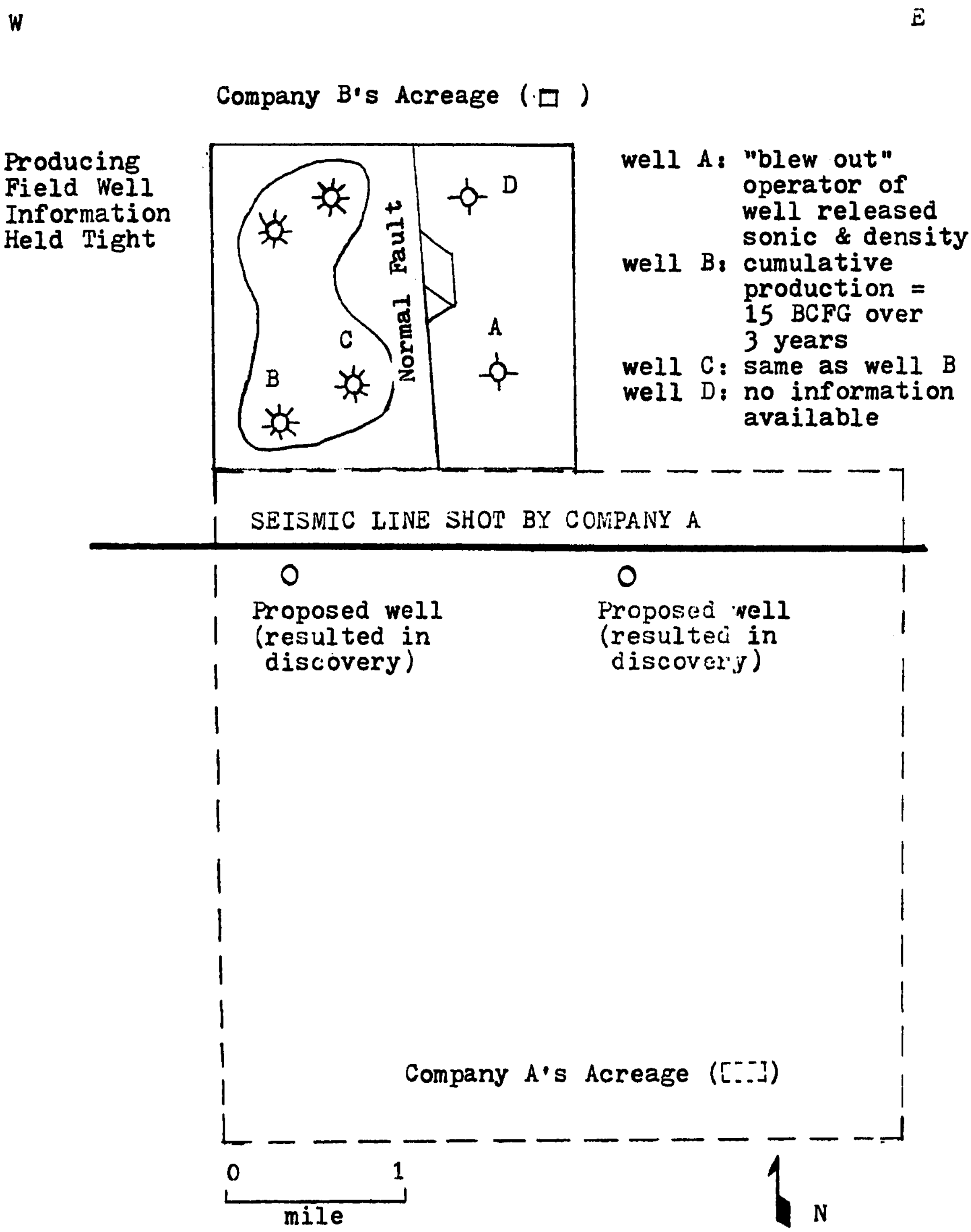


Figure 12. MODEL C: CASE STUDY

zone were encountered, the production would probably be much better than the already established good production in the field to the north, and, as mentioned earlier, the acreage position would weaken soon as leases began to expire.

Company A was undecided whether to shoot an east-west seismic line to evaluate their acreage or drill without seismic. Information on all the productive wells to the north was being held tight. The downthrown dry well A drilled by Company B, which had been logged (on an intermediate run) to the shale above the geopressured zone, had blown out. Both density and sonic logs had been released for this well.

Company A, decided to take the risk that no geopressured zones upthrown to the fault would be encountered and drill a test to 8000 feet without shooting seismic. If production were established, the well would hold the leases and the logs to be run would supply valuable information concerning velocity and density, which were unobtainable from the productive wells to the north, and which could be used for seismic reservoir modeling.

Subsequently, Company A drilled the test to 8000 feet and encountered a productive sand at approximately 7400 feet. The log run included density and sonic logs. Next, the company decided to shoot an east-west seismic line through their productive well and over their acreage to the east on the downthrown side of the fault.

After acquiring the seismic line, synthetic seismograms were made from the density and sonic logs from Company A's productive well and Company B's well which blew out.

The synthetic seismograms (traces made from well data to simulate seismic responses) generally matched the record (seismic) section from the east-west line which the company had shot, but no one knew the exact nature or character of the formations or the pressure conditions of the units below the logged interval downthrown to the fault. A careful study of the seismic and well data led the company to consider four plausible situations for the sequence on the downthrown side of the fault: a productive geopressured gas sand overlain by a geopressured shale (MODEL C, CASE 1), a normally pressured shale and gas sand (MODEL C, CASE 2), a geopressured shale and a water sand (MODEL C, CASE 3), and finally, a normally pressured shale overlying a tight sand (MODEL C, CASE 4). Company A decided to model these four above-mentioned situations, and if a good fit was found between the seismic line and one of their models, and if the model which fit the seismic indicated hydrocarbons with good pay potential, then the company would drill a well. The following discussion concerns the four models.

MODEL C, CASE 1

Geologic Setting

The first model to be discussed is a typical Miocene sequence of the Gulf Coast Province. It represents a growth-fault reservoir with interbedded tight sands and shales upthrown to the fault and with relatively thick sand accumulation on the downthrown side of the fault (Figure 13). The downthrown shale-sand sequence between approximately 7300-7600 feet, in the vicinity of the fault, is geopressured. The productive geopressured gas sand at 7600 feet is overlain by a geopressured shale which, in turn, is overlain by an impermeable shale. The gas sand is also sealed downthrown against a shale and tight sand, which are on the upthrown side of the fault.

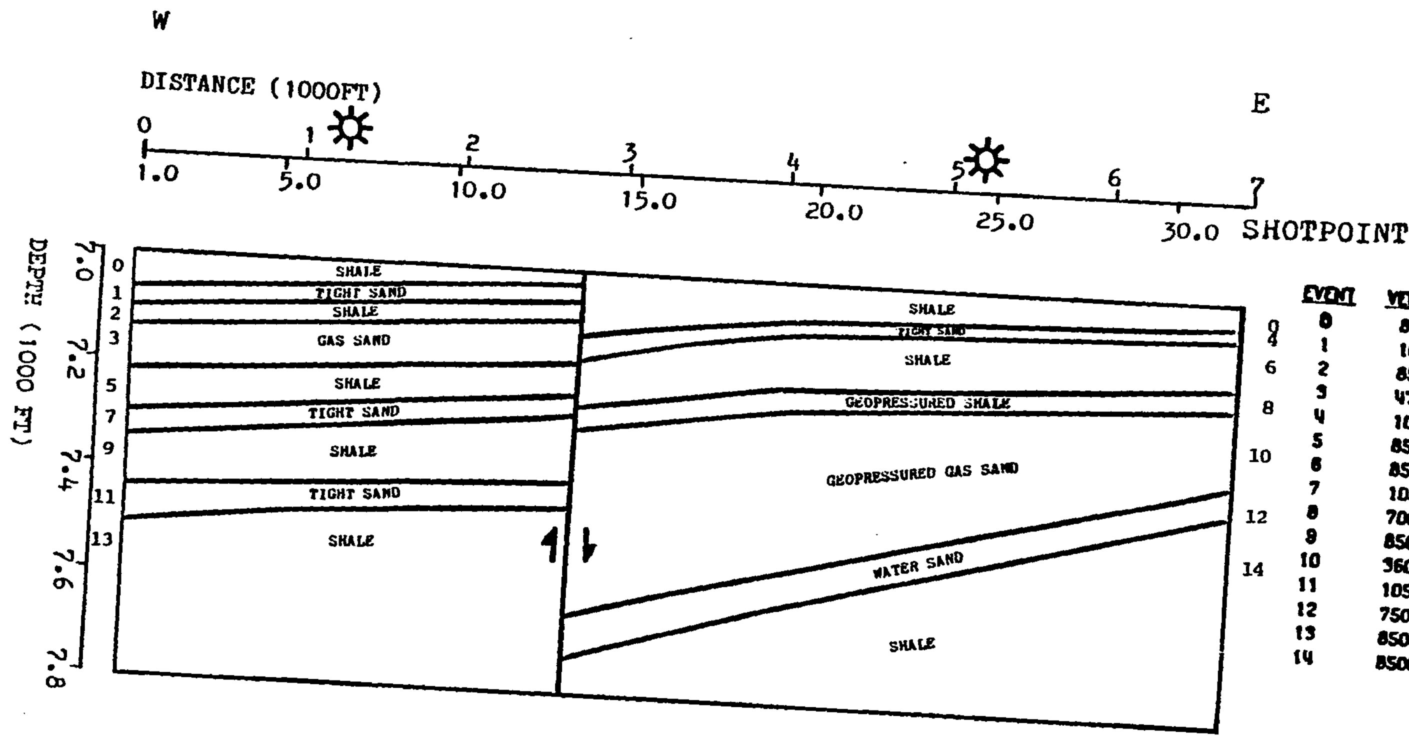
Reservoir Acoustic Parameters

Since the entire model encompasses only 800 feet of section, and velocities and densities over such a small geologic interval generally tend to remain relatively constant, the following values were assigned (Table 7):

Reservoir Model

The two-dimensional model of the reservoir described above is presented in Figure 14.

Table 8 shows the series of reflection coefficients generated at the interfaces in the model. Reflection coefficients range from -0.385 (top normally pressured gas sand) to 0.419 (base geopressured gas sand).



EVENT	VELOCITY	DENSITY
0	8500	2.55
1	10500	2.66
2	8500	2.55
3	4700	2.05
4	10500	2.66
5	8500	2.55
6	8500	2.55
7	10500	2.66
8	7000	2.20
9	8500	2.55
10	3600	1.96
11	10500	2.66
12	7500	2.30
13	8500	2.55
14	8500	2.55

Figure 13 Miocene Growth Fault Reservoir (Geopressured Shale and Gas Sand)

TABLE 7

Acoustic Parameters: MODEL C, CASE 1

Lithology	Velocity(fps)	Density(gms/cc)
impermeable shales	8500	2.55
tight sand	10500	2.66
water sand	7500	2.30
gas sand (normally pressured)	4700	2.05
gas sand (abnormally pressured)	3600	1.96

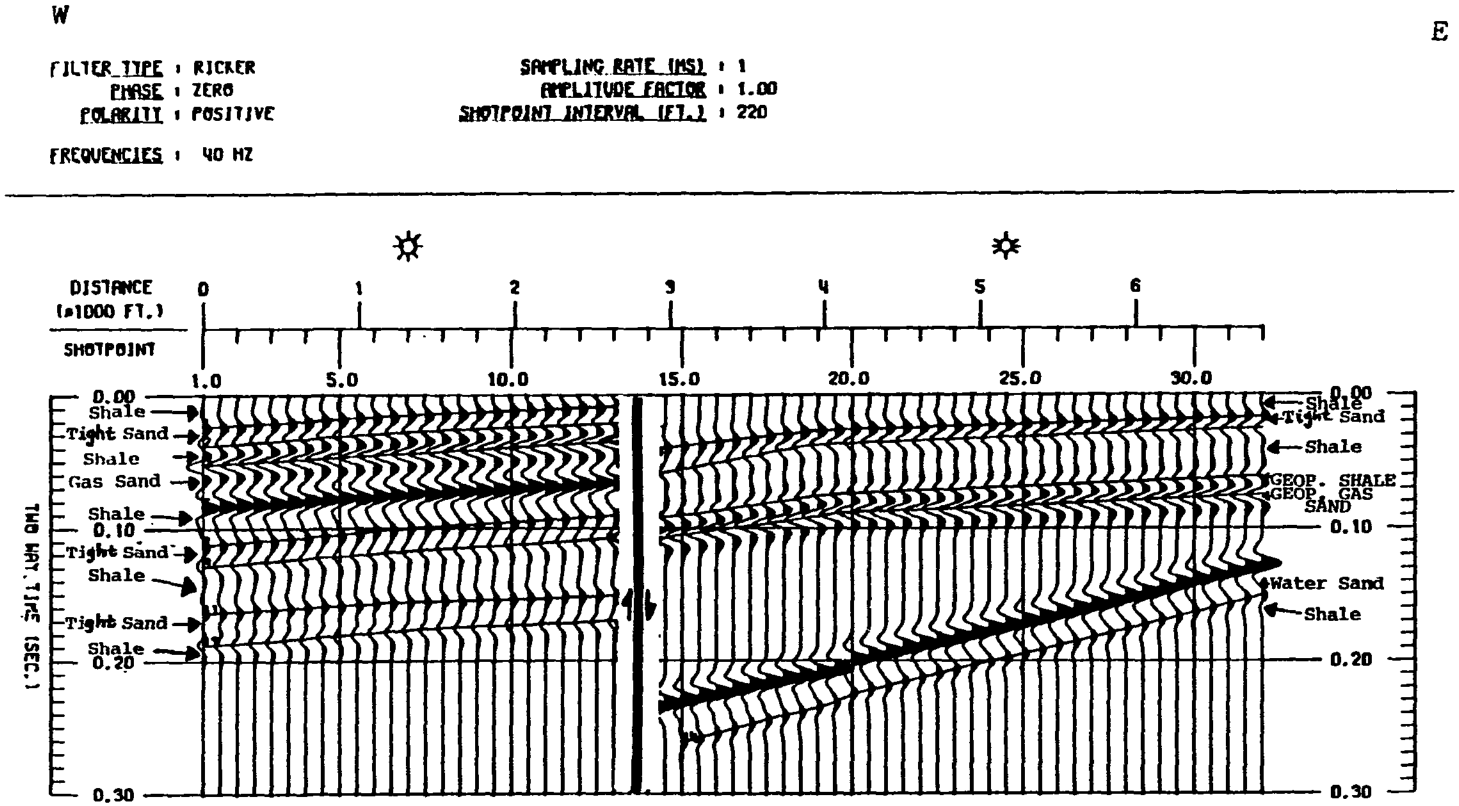


Figure 14 Seismic MODEL C: CASE 1; Miocene Growth Fault Reservoir (Geopressured Shale and Gas Sand)

TABLE 8

Reflection Coefficients: MODEL C, CASE 1

Horizon	Reflection Coefficient	Lithologic Top
1	0.126	Tight Sand(u)
2	-0.126	Shale(u)
3	-0.385	Gas Sand(u)
4	0.126	Tight Sand(d)
5	0.385	Shale(u)
6	-0.126	Shale(d)
7	0.126	Tight Sand(u)
8	-0.169	Geopressured Shale(d)
9	-0.126	Shale(u)
10	-0.371	Geopressured Gas Sand(d)
11	0.126	Tight Sand(u)
12	0.419	Water Sand(d)
13	-0.126	Shale(u)
14	0.114	Shale(d)

(u) = upthrown side of fault

(d) = downthrown side of fault

Discussion

The strongest reflection is generated at the contact between the base of the overpressured gas sand and the top of the water sand. Note that the top and bottom of each bed (Figure 14) is coincident with either a peak or trough. This is a function of the zero-phase assumption and the frequency of the wavelet. The geopressured shale, only approximately 50 feet thick, is totally resolved. The top of the geopressured shale has a negative reflection coefficient (therefore appears as a trough), while the base of the same shale, which is the top of the geopressured gas sand, also appears as a trough. At the bottom of the abnormally pressured gas sand is a peak, coincident with the top of the water sand. Note that as the water sand thickens toward the fault, an "extra" peak tries to develop, beginning at shotpoint 22 and at shotpoint 15, the peak is even more pronounced. This phenomenon is a function of the tuning thickness of the wavelet. Generally, the massive shale sequences are characterized by rather broad, low frequency events.

The upthrown portion of MODEL C, CASE 1 contains interbedded shales and tight sands with a productive gas sand at approximately 7250 feet. The gas sand encased in shales is resolved with a strong trough at the top and a strong peak at the bottom.

Ten years ago, the strong reflections at the bases of the gas sand (upthrown) and the geopressured sand (downthrown) would have been sufficient for many companies to drill two wells to test each of these "bright spots," simply because they were there. Today, the engineer and the geophysicist might ask the questions, "What combinations of acoustic impedance might cause these high amplitude events?" and "Are they worth drilling?" That is to say, seismic modeling has progressed to such an extent that even though the solutions are not unique, they can be useful in reducing risks.

Suppose MODEL A, CASE 1 is a seismic section. One of the more apparent characteristics of the section, other than the vertical fault, is the series of broad, low amplitude events, which happens to be the geopressured sand, on the downthrown side of the fault. Another obvious characteristic is the high amplitude nature of the events mentioned above (contacts). In terms of a seismic section, the obvious questions would become "What are the high amplitude events as well as the broad, low frequency events?" This case matched the seismic line shot by Company A quite well, but the company wanted to examine the other three aforementioned cases before drilling. Other possibilities for this sequence are investigated in MODEL C, CASES 2-4.

MODEL C, CASE 2

Geologic Setting

The second model is exactly like MODEL C, CASE 1 except that the geopressured shale at 7300 feet and the geopressured gas sand at 7400 feet have been replaced by a normally pressured shale and a normally pressured gas sand, respectively, of the same thicknesses (Figure 15).
Modifying the geopressured shale has the effect of adding approximately 50 feet of section to the overlying shale.

Reservoir Acoustic Parameters

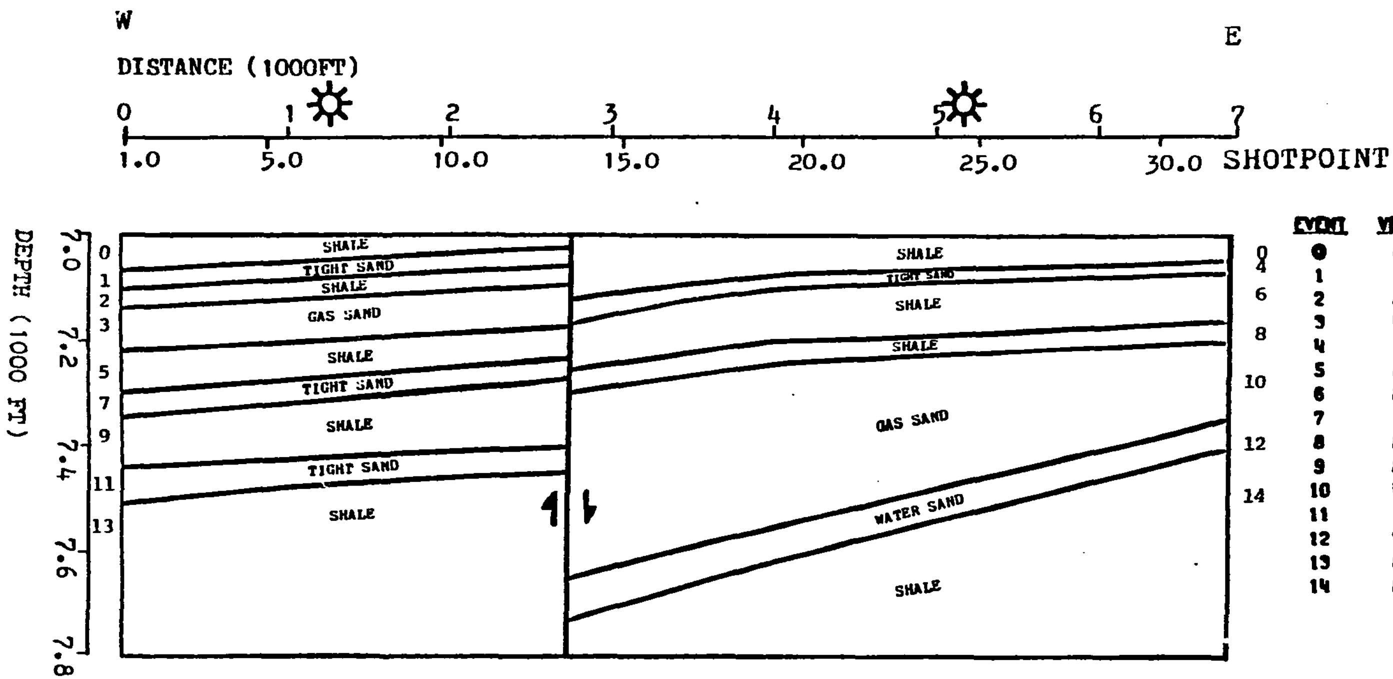
The velocities and densities are the same as in MODEL C, CASE 1. The geopressured shale (V = 7000 fps, ρ = 2.2 gms/cc) at 7300 feet, and the geopressured sand (V = 3600 fps, ρ = 1.96 gms/cc) at 7600 feet (MODEL C, CASE 1) have been changed to a normally pressured shale (V = 8500 fps, ρ = 2.55 gms/cc) and a normally pressured gas sand (V = 4700 fps, ρ = 2.05 gms/cc), respectively, in MODEL C, CASE 2.

Reservoir Model

The two-dimensional model of the reservoir described above is presented in Figure 16 . Table 9 gives the series of reflection coefficients generated at the interfaces in the model. Reflection coefficients range from -0.385 (top of upthrown normally pressured gas sand) to 0.385 (base of upthrown normally pressured gas sand; See Table 9) .

Discussion

Overall appearance of the normally pressured shale and



EVENT	VELOCITY	DENSITY
0	8500	2.55
1	10500	2.68
2	8500	2.55
3	4700	2.05
4	10500	2.68
5	8500	2.55
6	8500	2.55
7	10500	2.68
8	8500	2.55
9	8500	2.55
10	4700	2.05
11	10500	2.68
12	7500	2.30
13	8500	2.55
14	8500	2.55

Figure 15 Miocene Growth Fault Reservoir (Normally Pressured Gas Sand)

TABLE 9

Reflection Coefficients: MODEL C, CASE 2

Horizon	Reflection Coefficient	Lithologic Top
1	0.126	Tight Sand(u)
2	-0.126	Shale(u)
3	-0.385	Gas Sand(u)
4	0.126	Tight Sand(d)
5	0.385	Shale(u)
6	-0.126	Shale(d)
7	0.126	Tight Sand(u)
8	0.000	Shale(d)
9	-0.126	Shale(u)
10	-0.385	Gas Sand(d)
11	0.126	Tight Sand(u)
12	0.283	Water Sand(d)
13	-0.126	Shale(u)
14	0.114	Shale(d)

(u) = upthrown side of fault

(d) = downthrown side of fault

gas sand in MODEL C, CASE 2 (Figure 16) is similar to the abnormally pressured shale and gas sand of MODEL C, CASE 1 (Figure 14); however, critical distinctions exist. For example, the top of the normally pressured shale appears as a peak in CASE 2, whereas it appears as a trough in CASE 1; that is, there is a polarity reversal associated with the top of the shale. A second distinction is the amplitude difference between the base of the normally pressured gas sand and the abnormally pressured gas sand: the overpressured sand has a higher amplitude at its base. The third and perhaps most pronounced difference is the time variation between the two cases. For example, shotpoint 15 (CASE 1) shows a 125 millisecond thickness for the productive gas sand, whereas shotpoint 15 (CASE 2) shows a 96 millisecond thickness for the gas sand. The thicknesses (depthwise) of these sands are equivalent. This phenomenon (29 millisecond difference) is called a "velocity sag." In order to confirm this result, it is necessary to perform the following calculations:

<u>Abnormally</u> <u>pressured</u> <u>sand</u> (CASE 1)

Sand thickness = 225 feet (Shotpoint 15)

Interval velocity = 3600 fps

Sand time thickness = 125 milliseconds (two-way time)

Sand thickness (ft.) = Interval velocity x Time Thickness (one-way time)

= 3600 fps x 0.0625 sec

= 225 ft.

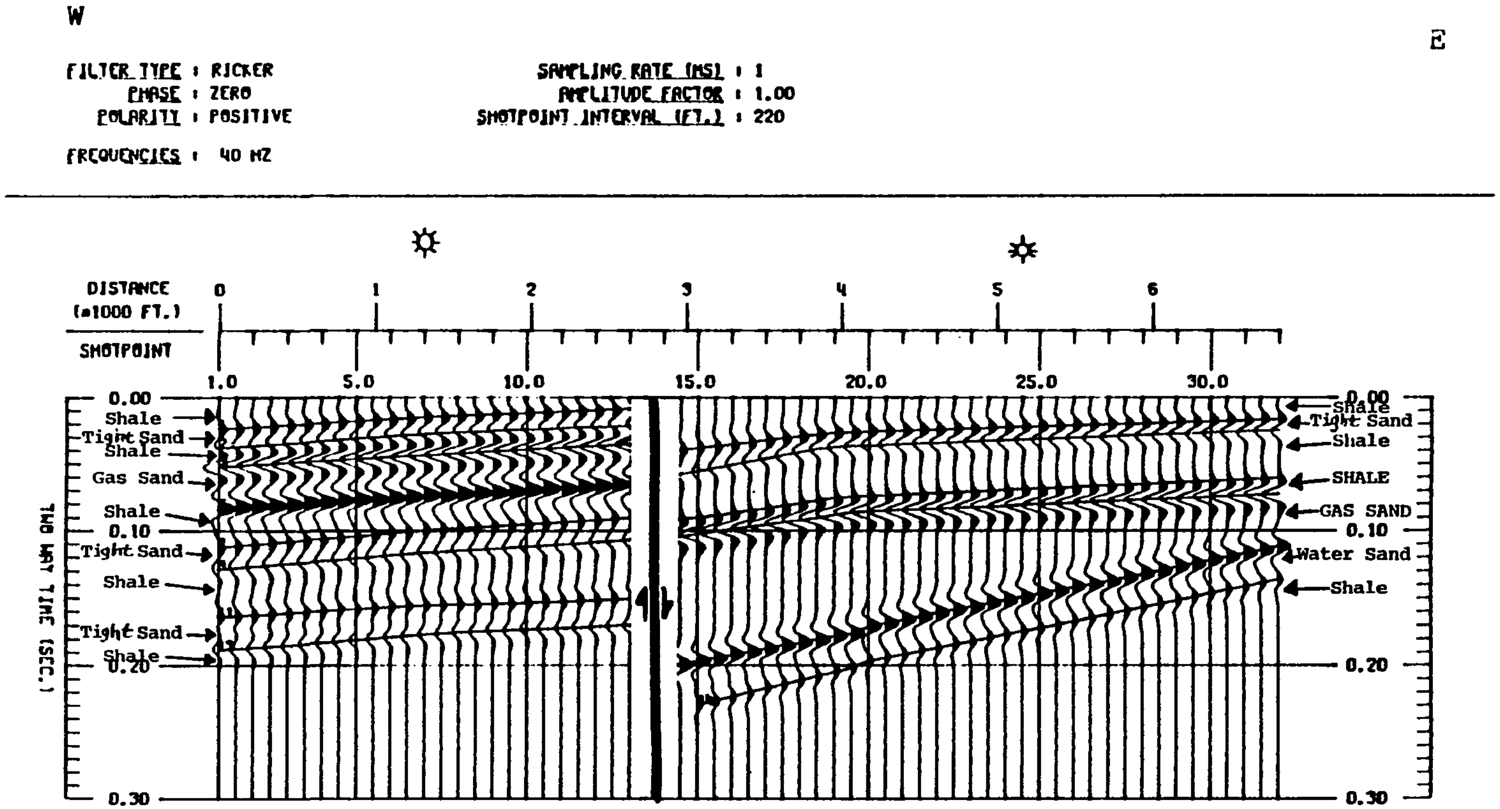


Figure 16 Seismic MODEL C: CASE 2; Miocene Growth Fault Reservoir (Normally Pressured Gas Sand)

Normally pressured sand (CASE 2)

Sand thickness = 225 feet (Shotpoint 15)

Interval velocity = 4700 fps

Sand time thickness = 96 milliseconds (two-way time)

Sand thickness (ft.) = Interval velocity x Time thickness (one-way time)

= 4700 fps x 0.0380 sec.

= 225 ft.

Since the thickness of 225 feet is the same in both cases, a velocity sag does exist.

Because of the polarity, amplitude, and travel-time variations between CASE 2 and the seismic section, Company A temporarily "ruled out" this situation.

MODEL C, CASE 3

Geologic Setting

This model is the same as MODEL A, CASE 1 except that the geopressured gas sand in CASE 1 has been replaced by a water sand (Figure 17).

Reservoir Acoustic Parameters

The geopressured gas sand ($V = 3600$ fps, $\rho = 1.96$ gms/cc) has been replaced by a water sand ($V = 7500$ fps, $\rho = 2.3$ gms/cc). This has the net effect of increasing the water sand thickness by approximately 100 feet.

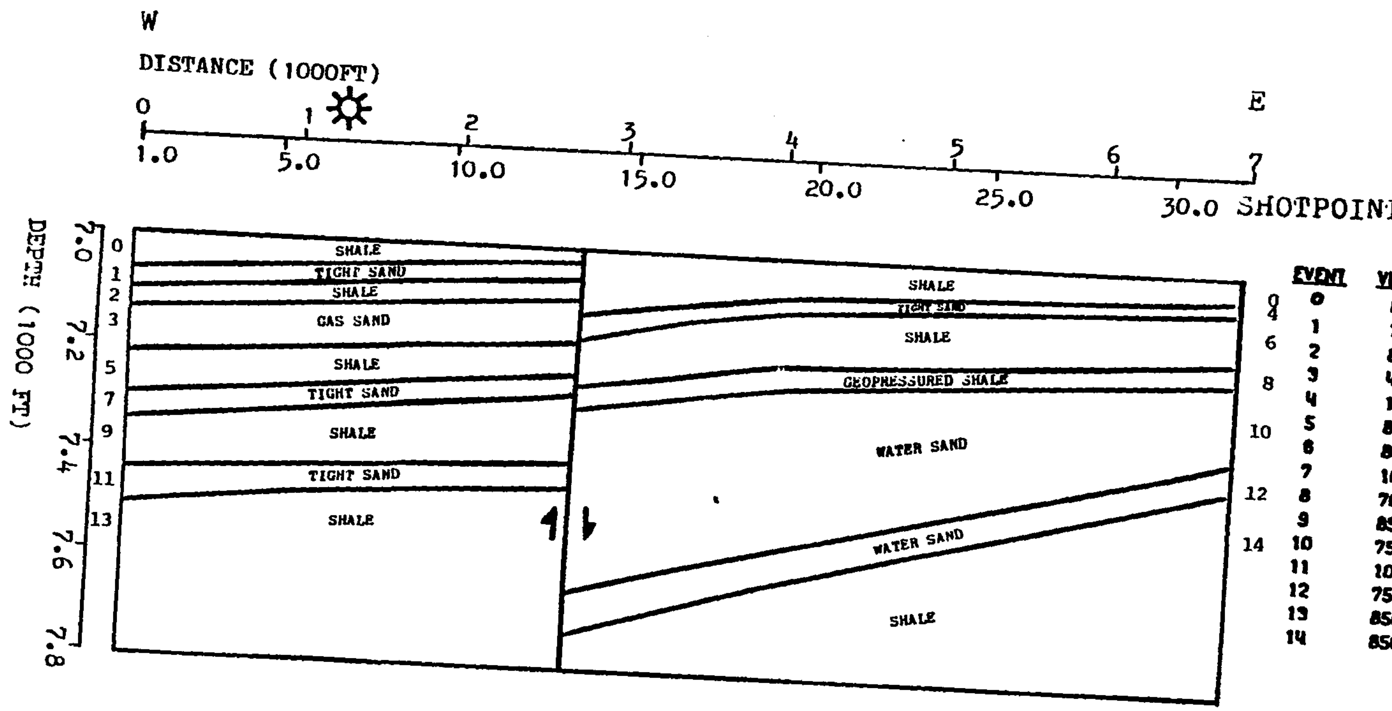
Reservoir Model

The two-dimensional model of the reservoir is depicted in Figure 18.

Table 10 shows the series of reflection coefficients generated at the interfaces in the model. Reflection coefficients range from -0.385 to 0.385.

Discussion

The water sand, which is bounded by a geopressured shale on top and by a normally pressured shale on bottom, shows very weak reflections at its boundaries. In terms of time thickness, the water sand appears to be more like the normally pressured gas sand of MODEL A, CASE 2; however, character-wise it matches neither CASE 1 nor 2. The top of the abnormally pressured shale (trough) is like CASE 1, but



EVENT	VELOCITY	DENSITY
0	8500	2.55
1	10500	2.66
2	8500	2.55
3	4700	2.05
4	10500	2.66
5	8500	2.55
6	8500	2.55
7	10500	2.66
8	7000	2.20
9	8500	2.55
10	7500	2.30
11	10500	2.66
12	7500	2.30
13	8500	2.55
14	8500	2.55

Figure 17 Miocene Growth Fault Reservoir (Geopressured Shale and Normally Pressured Water Sand)

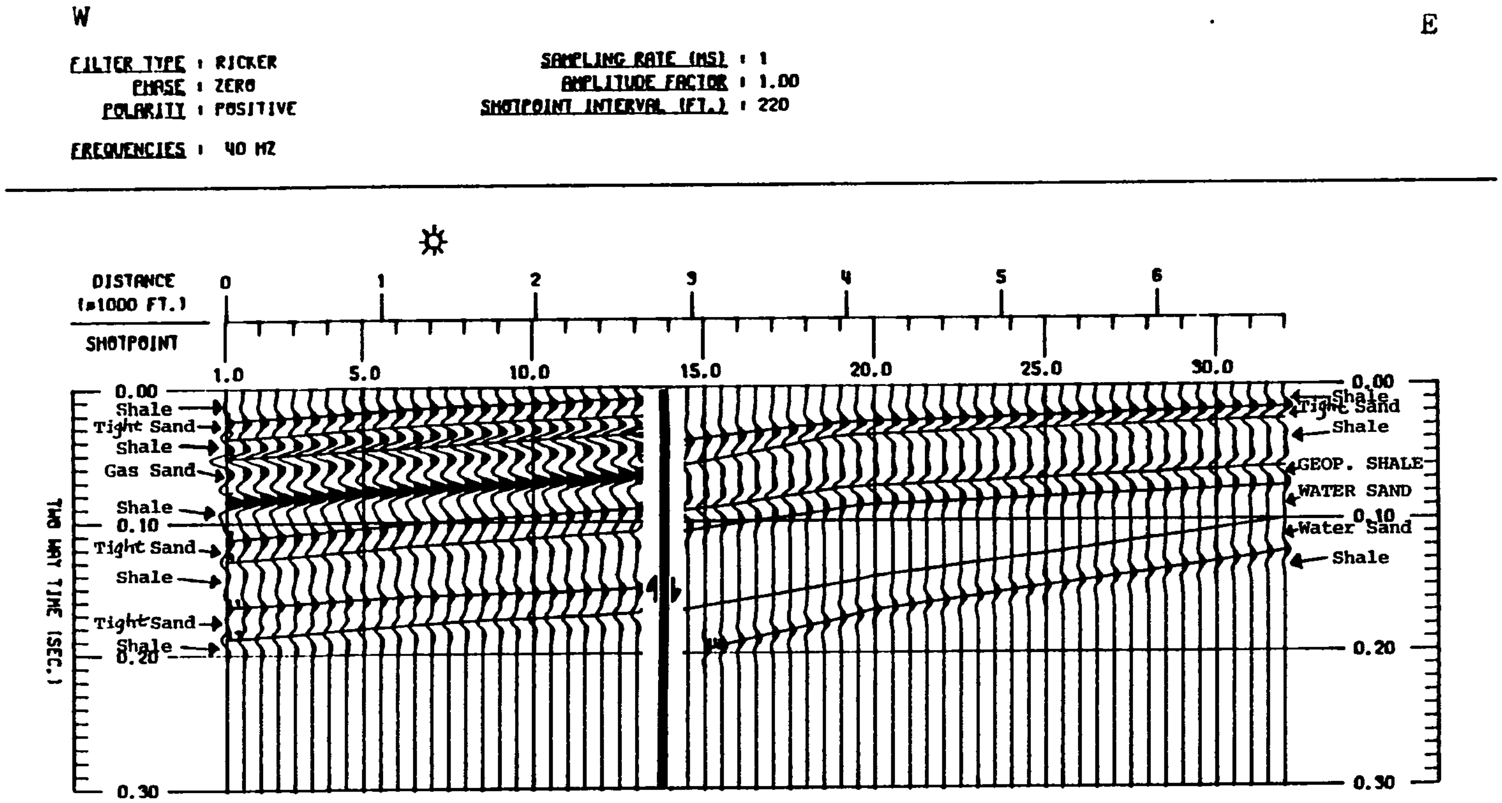


Figure 18 Seismic MODEL C: CASE 3; Miocene Growth Fault Reservoir (Geopressured Shale and Normally Pressured Water Sand)

TABLE 10

Reflection Coefficients: MODEL C, CASE 3

Horizon	Reflection Coefficient	Lithologic Top
1	0.126	Tight Sand(u)
2	-0.126	Shale(u)
3	-0.385	Gas Sand(u)
4	0.126	Tight Sand(d)
5	0.385	Shale(u)
6	-0.126	Shale(d)
7	0.126	Tight Sand(u)
8	-0.169	Geopressured Shale(d)
9	-0.126	Shale(u)
10	0.057	Water Sand(d)
11	0.126	Tight Sand(u)
12	0.000	Water Sand(d)
13	-0.126	Shale(u)
14	0.114	Shale(d)

(u) = upthrown side of fault

(d) = downthrown side of fault

its base is a trough, unlike the peaks in CASES 1 and 2. Overall, the reflection strengths of the geopressured shale-water sand sequence are considerably less than the first two cases in MODEL A.

These differences in polarity and amplitude are important clues in distinguishing between geopressured gas sands, normally pressured gas sands, and water sands. The thickness of the tight sand was considerably different than the response of the seismic section; thus, this case was rejected by Company A. The final case of MODEL C to be considered is a tight sand overlain by a normally pressured shale.

MODEL C, CASE 4

Geologic Setting

The only changes in this model are as follows: the abnormally pressured shale and water sand become a normally pressured shale overlying a tight sand (Figure 19).

Reservoir Acoustic Parameters

The geopressured shale (V = 7000 fps, ρ = 2.2 gms/cc) and the water sand (V = 7500 fps, ρ = 2.3 gms/cc) in CASE 3 have been replaced by a shale (V = 8500 fps, ρ = 2.55 gms/cc) and tight sand (V = 10500 fps, ρ = 2.66 gms/cc), respectively.

Reservoir Model

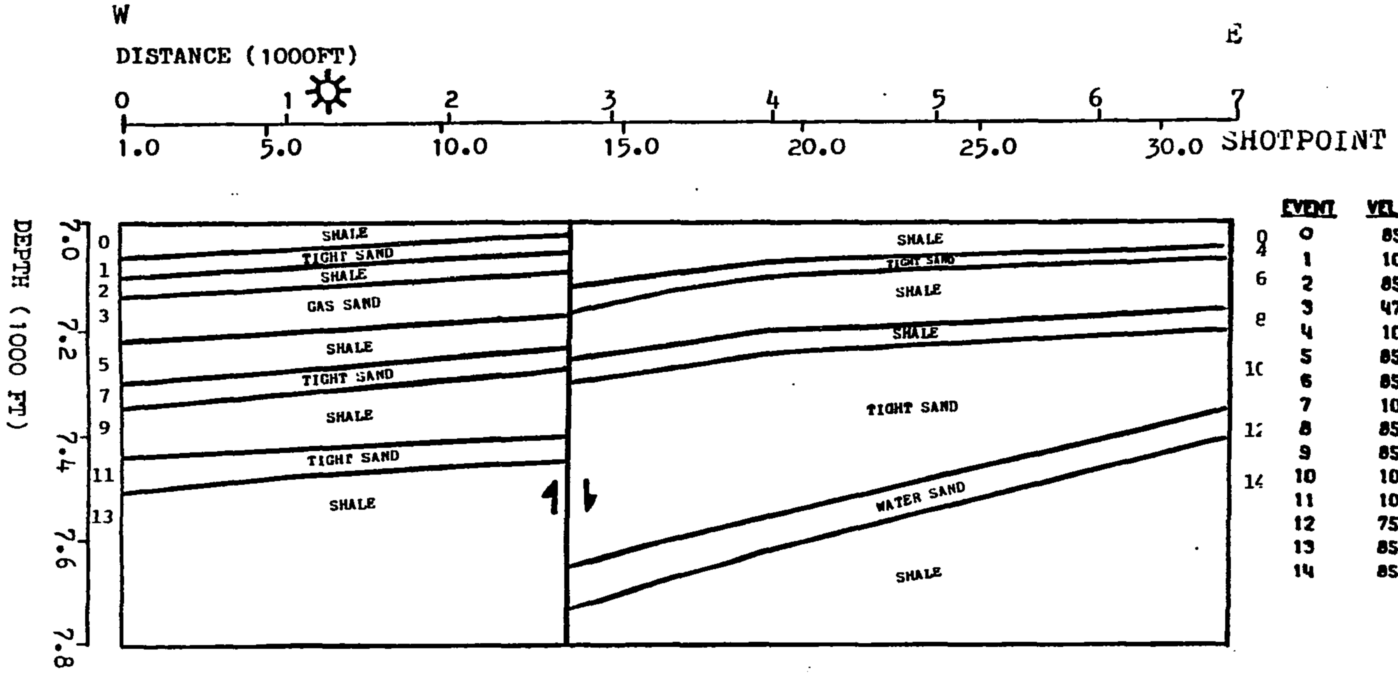
Figure 20 illustrates the two-dimensional seismic response of the above reservoir.

Table 11 shows the series of reflection coefficients generated at the interfaces in the model. Reflection coefficients for this model range from -0.385 to 0.385.

Discussion

The top of the tight sand has a 0.126 reflection coefficient (RC) while its base (or the top of the underlying water sand), whose RC is -0.236, is nearly twice as strong but opposite in polarity. Again, at Shotpoint 15, the tight sand thickness is 225 feet as in previous cases, but the time separation of only 43 milliseconds is due to the high interval velocity (10,500 fps) of the sand unit.

The variation in time thickness here is a major dif-



EVENT	VELOCITY	DENSITY
0	8500	2.55
1	10500	2.66
2	8500	2.55
3	4700	2.05
4	10500	2.66
5	8500	2.55
6	8500	2.55
7	10500	2.66
8	8500	2.55
9	8500	2.55
10	10500	2.66
11	10500	2.66
12	7500	2.30
13	8500	2.55
14	8500	2.55

Figure 19 Miocene Growth Fault Reservoir (Normally Pressured Tite Sand)

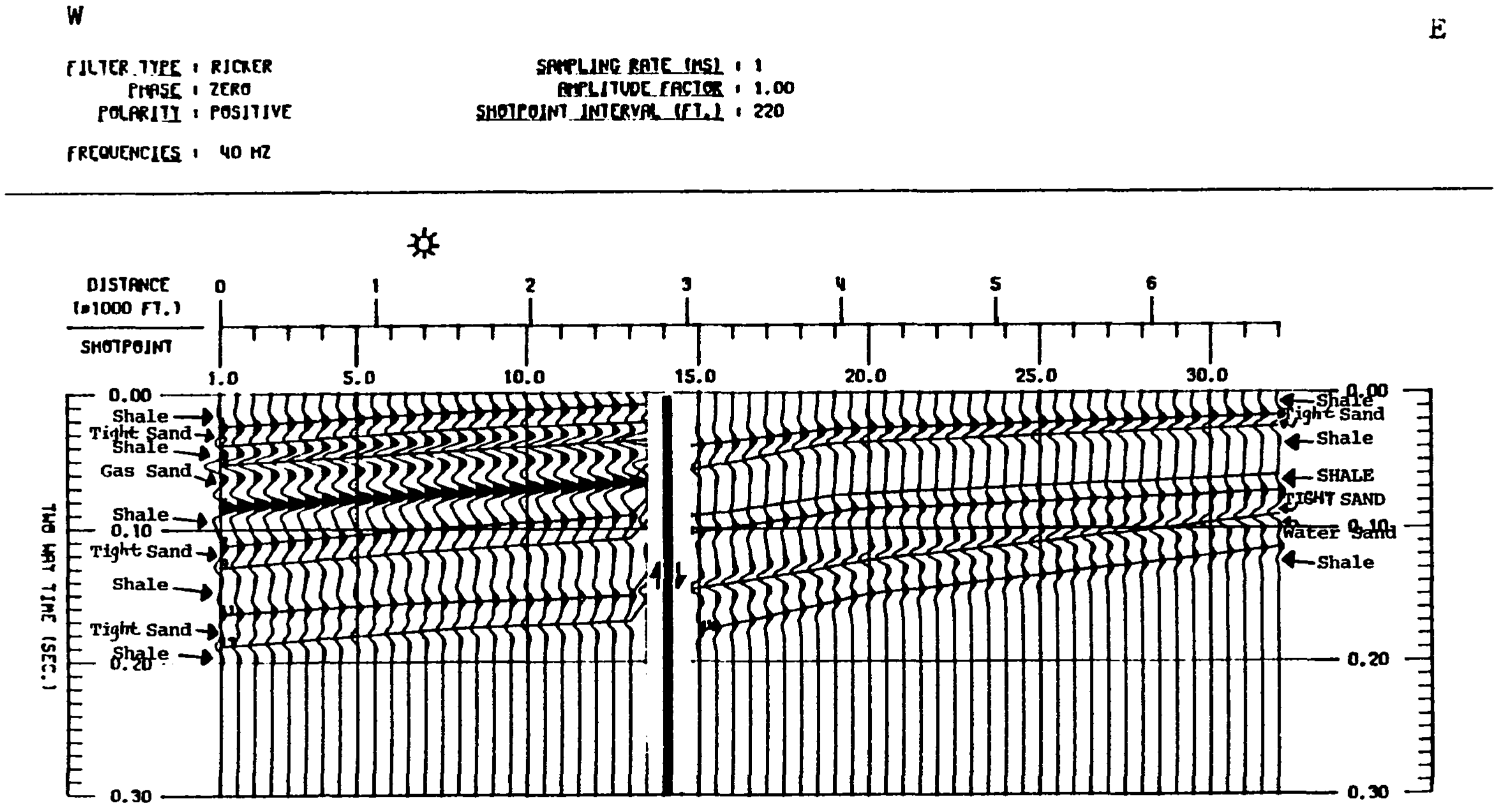


Figure 20. Seismic MODEL C: CASE 4; Miocene Growth Fault Reservoir (Normally Pressured Tite Sand)

TABLE 11

Reflection Coefficients: MODEL C, CASE 4

Horizon	Reflection Coefficient	Lithologic Top
1	0.126	Tight Sand(u)
2	-0.126	Shale(u)
3	-0.385	Gas Sand(u)
4	0.126	Tight Sand(d)
5	0.385	Shale(u)
6	-0.126	Shale(d)
7	0.126	Tight Sand(u)
8	0.000	Shale(d)
9	-0.126	Shale(u)
10	0.126	Tight Sand(d)
11	0.126	Tight Sand(u)
12	-0.236	Water Sand(d)
13	-0.126	Shale(u)
14	0.114	Shale(d)

(u) = upthrown side of fault

(d) = downthrown side of fault

ference between this case and CASES 1-3. Further, if this model were a real seismic section, seismic reflection character on the downthrown side of the fault would not point to any "bright spots" which should be investigated, and this case did not match Company A's seismic line. For these reasons, the managers of Company A ruled out this case as a possible geologic model for the downthrown well.

MODEL C SUMMARY AND COMPANY A'S DECISION

Of the four cases described above, the best fit between the synthetic seismic model and Company A's seismic line was CASE 1: a geopressured gas sand overlain by a geopressured shale. Results of the modeling indicated a possible 50-feet thick geopressured shale at 7,300 feet, overlying an overpressured gas sand 200 feet thick; thus, the mud weight would need to be increased at approximately 7200 feet.

Company A decided to drill a well at Shotpoint 24 (Figure 14) to test the idea and to hold their leases. In terms of thickness, depth, lithology and pressure conditions, the well came in very close to predictions by the seismic modeling of the reservoir and flowed 15 million cubic feet of gas per day.

Additional seismic modeling delineated the lateral extent of the two major reservoirs and resulted in a near-perfect well completion percentage on the company's acreage holdings.

This CASE STUDY mentioned above is just one example of how seismic modeling can aid the engineer in designing wells and thereby save companies thousands of dollars and, more importantly, save human lives.

The following chapter is a summary and lists conclusions from this research.

CHAPTER V

APPLICATIONS

Now that the results of three models, involving eight distinct reservoir situations, have been discussed, it is important to examine the broader aspects of reservoir seismic modeling. The direct applications of this research will be presented in the summary.

Seismic modeling is an important engineer's tool for understanding the behavior of reservoirs. The traditional philosophical approach to the exploration and development of hydrocarbons has been to define structural type traps first and search for the stratigraphic traps if "all else fails." Due to the fact that many of the so-called "easy" reservoirs have already been found, industry is looking toward finding new, complex stratigraphic plays in rank wildcat areas or in areas which have been overlooked by previous drilling. Fields such as EAST TEXAS (the largest stratigraphic field ever found), which was discovered by chance, and which at the time of its discovery was the largest in the western hemisphere (Halbouty[19], 1982), have become important analogs for future exploration and development of hydrocarbons.

Additionally, seismic modeling currently plays a significant role in the oil and gas industry's four major areas of concern: exploration, development, production, and leasehold (land acquisition):

(1) In exploration, seismic modeling can be applied to defining structure and stratigraphy of a given area by mapping faults, anticlines, synclines, noses, facies changes, and porosity changes,

(2) In development, the reservoir engineer can use modeling to delineate vertical and lateral extents of hydrocarbon accumulations by mapping sand and carbonate geometry along with fluid saturant contacts. A drilling engineer might use reservoir modeling in estimating mud weights to be used for a well and in defining drilling hazards (such as geopressured zones or areas of shale flowage),

(3) A company's production group finds modeling (actually a form of reservoir simulation) beneficial in defining reservoir limits for secondary or tertiary recovery, and

(4) A land department might use modeling for recommending additional leasehold purchase or evaluating acreage submittals.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Occurrence of geopressured reservoirs has been documented on five continents and they are known to occur in rocks ranging from Cambrian to Recent in age (Dorfman & Kehle,[12] 1974). Because of their associated high pressures, these zones are hazardous to drill, yet they contain prolific producing zones in many cases. This study involves reservoir seismic two-dimensional modeling of three different types of abnormally pressured zones including: a lenticular sand sequence, a channel sand unit, and a growth fault reservoir.

MODEL A, CASE 1, a walk-through example to acquaint the reader with seismic modeling, represents three overpressured Oligocene Gulf-Coast lenticular sands, ranging from 0-60 feet in thickness, encased in a massive shale sequence at an approximate depth range of 5,000-5,500 feet. Results from the synthetic seismic model demonstrate that the sands are totally resolved, with the tops of the sands corresponding to peaks and their bases corresponding to troughs. The bases of the sands are "bright spots."

MODEL A, CASE 2 represents three discrete normally pressured tight sands with the same thicknesses and geometries as in CASE 1. The sands are totally resolved, opposite in polarity to those in the first case, and show distinct velocity "pullups." The normally pressured sands have higher velocities and densities than their geopressured counterparts.

MODEL B, CASE 1 represents a typical Pennsylvanian (Mid-Continent) geopressured channel sand sequence encased in shales and limestones at approximately 12,500-13,000 feet. As in MODEL A, CASES 1-2, sand geometry is reflected by the synthetic section. Both sands are resolved in terms of peak and trough separation.

MODEL B, CASE 2 is the same in terms of unit thickness and geometry as CASE 1, except that all the geopressured zones are normally pressured. Neither of the channel sands are resolved by peak and trough separation.

MODEL C is a case study to demonstrate how a company successfully employed reservoir modeling to predict a geopressured zone, establish production and hold their leases. MODEL C, CASE 1 represents a typical Miocene Gulf Coast growth-fault reservoir with a productive geopressured sand in a predominantly sand-shale sequence downthrown and a productive normally pressured gas sand upthrown. Reflection coefficients range from -0.385 at the top of the upthrown normally pressured gas sand to 0.419 at the base of the geopressured gas sand (bright spot). The top and bottom of each bed in the model is totally resolved.

In terms of the geologic model, MODEL C, CASE 2 is exactly like MODEL C, CASE 1 except that the geopressured shale at 7300 feet and the geopressured gas sand at 7400 feet have been replaced by a normally pressured shale and a normally pressured gas sand, respectively, of the same thicknesses and geometries. Reflection coefficients range from -0.385 at the top of the upthrown normally pressured gas sand to 0.385 at the base of the upthrown normally pressured gas sand. Polarity, amplitude, and time thickness (resulting from a "velocity sag") are different for CASES 1 and 2.

MODEL C, CASE 3 contains a water sand overlain by a geopressured shale (downthrown). The two-dimensional reservoir model demonstrates reflections which are generally lower in amplitude and different in character compared to CASES 1 and 2.

Finally, CASE 4 of MODEL C, in which the abnormally pressured shale and water sand become a normally pressured shale overlying a tight sand, lacked bright spots and the individual sand and shale units were much thinner (travel-time-wise) than CASES 1 and 2.

Summarizing MODEL C, CASES 1-4, distinct differences in seismic character, polarity, frequency, amplitude, and travel-time thickness allow one to distinguish among normally pressured gas sands, abnormally pressured gas sands, tight sands, and water sands.

The following conclusions can be established from this study:

(1) Abnormally low velocities and densities (a result primarily from high porosities) are characteristic of overpressured zones,

(2) Geopressured reservoirs such as the Oligocene lenticular sands and the Miocene growth-fault sands, both of the Gulf Coast Province, and the Pennsylvanian channel sands of the Mid-Continent can be seismically modeled using velocity and density as the major acoustic parameters,

(3) The velocities and densities mentioned in (1) allow one to distinguish between abnormally pressured versus normally pressured sands, of the same geologic setting (ie., same thickness and geometry) as demonstrated by MODELS A,B, and C,

(4) MODEL C (channel sands of the Mid-Continent) demonstrates that abnormally pressured and normally pressured gas sands, along with tight sands and water sands, have different seismic characteristics for the same structural and stratigraphic configurations,

(5) Variations in seismic character, polarity, frequency, amplitude, and travel-time are useful attributes in distinguishing overpressured versus normally pressured sands,

(6) Seismic modeling is an important tool for the engineer in determining depth, thickness, and lateral extent of an abnormally pressured zone,

(7) Reservoir seismic modeling is useful in properly designing wells in geopressured areas (eg., determing when excessive mud weight might be necessary),

(8) Geopressured reservoir modeling can save human lives, and

(9) Based upon the author's knowledge, this research is the first attempt to illustrate modeled seismic responses from three different types of geopressured reservoir traps, and is the first comprehensive published attempt to demonstrate the important applications of seismic modeling to known occurrences of geopressured zones.

Concerning abnormally pressured zones, this research is just a beginning. Each reservoir case is unique, due to vertical and lateral changes in the rock and fluid properties, and must be treated as such. The "average" or accepted values of velocity and density for the three different geologic settings in this paper will probably change within each given area. The importance of this study is not the values of the acoustic parameters which were used, but rather that it is an attempt at demonstrating that seismic modeling <u>is</u> an important tool to the engineer, that this tool can be useful in distinguishing abnormally versus normally pressured gas sands, and finally, that reservoir modeling can save oil and gas companies thousands of dollars and perhaps, tens of lives. From these standpoints, the author challenges those interested persons to document geopressured trapping mechanisms via seismic modeling and publish their findings so that others might benefit.

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