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Seismic HC reservoir prediction: A (Critical) Review on the Determination Of Lithological Parameters from Seismic Data

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Abstract: The approach in seismic reservoir prediction is a combination of the extraction of physical parameters from seismic measurements, seismogram inversion including the calibration at available well locations and modelling. The key to most present-day reservoir interpretation is understanding the reflection wave shape as a function of structural and petrophysical parameters.

Much success in the recognition of stratigraphical traps, prediction of pore filler changes and the extent of hydrocarbon reservoirs from seismic sections during the last decade is based on improvements in seismic data acquisition plus processing and a better understanding of the relations between seismic surface data and petrophysical/lithological situations in the subsurface

After a brief review on new developments and trends in Exploration Seismics, the concepts of data extraction and modelling, the conditions required for their application and limitation are discussed.

INTRODUCTION

Seismic reservoir prediction can be classified into at least three different problems:

- identification of stratigraphic traps,
- prediction of pore fillers,
- and the prediction of the extent of hydrocarbon reservoirs.

The geophysical approach to solve the different problems is a combination of the extraction of the physical parameters, especially interval velocity and acoustic impedance from seismic sections, the lithological and petrophysical calibration of the physical parameters at available well locations and interactive modelling based on the understanding of the reflection wave shape as a function of structural and petrophysical parameters.

The term 'critical' in the title of the paper is put into brackets, as the following comments on Seismic HC Reservoir Prediction are not intended to discourage the use of seismic data for reservoir prediction, but to keep the limitations of the concept in mind.

NEW DEVELOPMENTS IN EXPLORATION SEISMICS

Much of the success in seismic reservoir prediction during the last decade has been based on improvements in seismic data acquisition plus processing (Bortfeld, 1983) and a better understanding of the relationship between seismic surface data and petrophysical/lithological situations in the subsurface via synthetic seismograms

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(Helbig, 1982). The most significant developments and trends in Exploration Seismics especially for reservoir prediction are:

- 1. A higher sampling of the subsurface using high frequency signals,
- 2. The combination of different exploration tools which enables the utilization of additional physical parameters, characterizing the reservoirs as for example the shear wave velocity.
- 3. Geophysical measurements in the direct vicinity of the targets.

3D Seismic

The higher sampling of the subsurface with broadband signals has led to an improvement in vertical and horizontal resolution, which is the prerequisite for reservoir prediction.

The number of recording channels is steadily increasing, both for land and marine operations, in order to provide for better spatial sampling. It is the intention to achieve a pointsource/pointdetector situation and to avoid smearing effects. This is particularly important for the recognition of lateral changes in lithology, porosity or direct hydrocarbon indicators.

There is a definite trend towards increasing usage of 3D techniques. These surveys are now firmly established in the detailed investigations of prospects.

Interpretation is aided tremendously by the availability of sections at any position and in any direction. This permits the consistent and reliable identification of very small structural features, as for example the exact identification of the fault pattern for a better delineation of the reservoirs at the beginning of the field development phase. Indeed most 3D seismic work is done with development objectives.

Figure 1 shows an offshore example of a gas sand interpretation based on 2D and 3D techniques (Galbraith and Brown, 1982). Major differences exist between the 2D and 3D interpretations. The 3D seismic has changed the fault pattern. Development drilling has to be initiated in a different fault block which is located further to the west from the one proposed from 2D data.

The Gas Water Contact at the well is deeper than the structural spill point. This involves a stratigraphic reservoir boundary in the SE. The validity of this boundary is indirectly confirmed by the results of seismic trace inversion. The results of a NW-SE orientated line, running through well P3, are shown on Figure 2 with an abrupt lateral velocity change between SP67 and SP79 which is interpreted as the stratigraphic reservoir boundary which separates a porous gas sand from a tight sand. In addition, horizontal seismic sections, as shown on the right side of Figure 1, offer the ability to view directly the spatial distribution of seismic parameters such as amplitude and velocity. These then permit the recognition of subtle stratigraphic features, as for example in the case the recognition of the stratigraphic reservoir boundary which is indicated by the change to strong (black) amplitudes.



Fig. 1. A Gas Sand Offshore Trinidad: Comparison of maps prepared by 2-D and 3-D techniques (including a horizontal seismic amplitude section at the same depth level) showing the marked improvement obtained by the use of 3-D techniques (from a GSI advertisement in *Geophysics*, December 1981).



Fig. 2. Results of Seismic Trace Inversion for a NW-SE orientated Line across the Prospect of Figure 1. The lateral change of the estimated acoustic impedance between SP 67 and SP 79 at the reservoir level indicates a stratigraphic boundary (from a GSI advertisement).

Field examples by different contractors are published where the horizontal sections of 3D seismic results permit depositional features, such as bars and channels, to be followed in detail. One of the examples is shown in Figure 3.

There have been increasing incentives to use 3D seismic to delineate the stratigraphic and lithologic characteristics of HC reservoirs and associated aquifers and to guide development drilling in order to minimise costs. However, much development work remains for the future. This includes 3D veolocity analysis, 3D migration as well as 3D static correction.

Shear wave seismic

Great efforts are presently undertaken by several oil companies and their contractors to develop the shear wave technology to its ultimate limits of applicability and precision in order to supplement the information derived from compressional waves.

In principle, shear waves offer at least two advantages for reservoir prediction:

- a. For shear waves one can expect a higher resolution in comparison to P-waves due to the shorter wavelength for comparable frequencies.
- b. The S-to P-wave velocity ratio has turned out to be a useful and assessing the few published field examples—also powerful indicator of lithology and porefiller changes, due to the different behaviour of the P- and S-wave velocities as a function of layer characteristics. Shear waves for example are quite helpful for the confirmation of bright spots identified on P-wave sections. As the shear wave velocities are porefiller independent, one cannot expect for gas sands bright spots in S-sections. If, however, the P-wave bright spots are caused for other reasons, for example by a change of facies, then the acoustic impedance changes for P-waves as well as for S-waves.

Shear wave surveys, in which horizontal vibrators, horizontal impacts or explosions are used, are today offered by several geophysical contractors.

Although the improvements in the development of shear wave generators during the last few years are quite impressive, there are several restrictions for a routine application of shear waves:

- A direct S-wave generation and recording is only applicable in onshore areas. A few contractors, therefore, try to make use of converted waves in offshore areas.
- Lateral variations of near surface velocities are much larger for S-waves than for P-waves; this results in considerable static and processing problems;
- The theoretically expected higher resolution of S-waves seems to be compensated by more elastic effects, in comparison to P-waves.

The next two figures show shear wave records. The single 120 trace record in Figure 4 demonstrates the large requirements for data processing for the extraction of



Fig. 3. Horizontal Seismic Section over a whole Prospect Area showing a Meandering River Channel (from a GSI advertisement).



Fig. 4. 120-Trace Shear Wave Seismogram

Source: Shear Wave vibrator

Receivers: Horizontally orientated geophones perpendicular to the direction of the wave propagation.

Vertical Stacking: 8 fold

Geophone Group interval: 5 m

Dynamic range of colour scale: 84 dB (from a Prakla-Seismos advertisement).

shear wave reflections. In Figure 5 a comparison between a P-wave section and an S-wave section is shown. The time scale of the P-wave section has been doubled to achieve a rough match of the travel times.

Data quality of shear wave sections which is comparable to P-sections, as in the shown example, is still the exception. The Signal to Noise ratio is generally lower than for P-wave measurements and much more headwaves are generated. Only after further improvements of the field technique and in processing, can full use be made of the advantages which S-waves offer in principle for reservoir prediction.

Vertical seismic profiling

Measuring the wavefield in the subsurface as is done by Vertical Seismic Profiling (VSP) offers several advantages in comparison to surface measurements. Figure 6 shows the principle of Vertical Seismic Profiling with seismic sources at the surface and geophones located in the borehole.

The main advantages of this field technique are:

- a. The deep reflections are the primary events of the upgoing wavefield and therefore easy to identify in sections where the upgoing wavefield is separated from the downgoing wavefield. In addition, the reflections are less influenced by multiples.
- b. VSP records show improved resolution as the disturbing near-surface layers are passed only once by the wavefield. The improvement can be seen in Figure 7 where a VSP section measured in a deviated well is compared with a seismic section measured at the surface. The VSP section gives much more details of the discontinuity of the seismic horizons and the fault pattern.
- c. Vertical Seismic Profiling offers the possibility to predict the reflectors below the bottom of the well much clearer than from surface measurements. The reasons are again: the vicinity of the geophones to the target and the elimination of all multiples in the upgoing wavefield of all layers above the deepest geophone.
- d. Lateral high resolution prediction away from the well can be done if dipping layers exist or if special field arrangements with offset source or deviated wells are used.

The applications of the method are numerous, however, at the present time they are primarily orientated towards structural evaluation, for example the determination of the dip of layers, of faults in the vicinity of wells or the evaluation of the structure beneath deviated wells. Apart from improving deep seismic data, the technique is being used to obtain a better understanding of wave propagation, attenuation and anisotropy. However, the use of VSP's for the determination of rock properties is not widely practiced today and only very few field examples are published showing the prediction of acoustic impedance changes both vertically and laterally.



Fig. 5. P- and S-wave Correlation. The time scales for the two sections are different (from a CGG advertisement).







Fig. 7. Comparison of Vertical Seismic Profiling Results from a Deviated Well and the corresponding Seismic Section measured at the Surface (from a SSC advertisement).

Summarizing the brief discussion on new developments and trends in Exploration Seismic one has to state that the most significant improvement for the prediction of HC-reservoirs during the last few years has been achieved in seismic resolution, while other very promising methods, as for example the shear wave method and Vertical Seismic Profiling are to be regarded as being still in the development stage.

The improvements in seismic resolution have encouraged more and more geophysicists, geologists and exploration managers to tackle the problems of seismic prediction, especially to predict the lateral extent of reservoirs and porefill changes, but also to look for stratigraphic traps, with quite different rates of success, however.

The following comments on the determination of physical parameters as lithological indicators from seismic data are intended to explain the reasons for success or failure.

COMMENTS ON THE DETERMINATION OF PHYSICAL PARAMETERS AS LITHOLOGICAL INDICATORS FROM SEISMIC DATA

Physical parameters deduced from seismic data for reservoir prediction are first of all interval velocities and acoustic impedances.

Determination of Interval Velocities from Seismic Data

Some geophysicists maintain that velocity analysis is a mature method, others state quite the contrary. Opinions about existing procedures for interval velocity determination also differ widely. These opinions are all biased by the precision and resolution desired. This is particularly true for 3D-velocity analysis.

For the petrophysical interpretation of seismic velocities one has to keep in mind that the expected error in interval velocity is proportional to the error of the stacking velocity, multiplied by a factor which is proportional to the ratio of depth to layer thickness (Schneider, 1969). Figure 8 shows the expected error of interval velocities as a function of the RMS-velocity error for different ratios of depth to layer thickness. For a depth to thickness ratio of 10 and an expected RMS-velocity error of 25m/sec the expected interval velocity error becomes already 300 m/sec.

The error in the determination of interval velocities from seismic data is in the order of 5 to 15%, depending on the signal to noise ratio, the geometry of the target and the parameters of the seismic field measurements. This means that the accuracy of interval velocity determinations for example for a layer with an interval velocity, of 3000 m/sec is approximately between ± 150 m/sec and ± 450 m/sec.

Therefore, one can imagine that for certain depth intervals for example of the Malay Basin, where the sand and shale velocities are comparable or even almost identical, predictions of lateral lithology changes from extracted interval velocities are hardly reliable. Also, the prediction of porefill changes from seismic velocities becomes a problem at least for greater depth as the velocity change for example for a sand layer



Fig. 8. Expected Error in Interval Velocity as a Function of RMS-Velocity Error and Depth to Layer Thickness Ratio (after W.A. Schneider, EAEG 1969).



Fig. 9. Pseudo Velocity Section from an Offshore Prospect in a Tertiary Sand/Shale Environment (from a CGG advertisement).

at a depth of 2000 m is only in the order of the expected error of the interval velocity if the water is replaced by oil or gas.

For complex geological structures the situation can still be worse, as the determination of interval velocities from seismic data is based on a number of approximations and the reliability of the results depends on the deviation of the actual conditions from the model.

The most serious effect is due to deviation from the vertical homogeneous model. Only if the interval is reasonably homogeneous will the estimated interval velocity be close to the true average velocity of this interval.

Even if this condition is satisfied a number of warning notes are necessary for situations with discordant top and base layers or dipping layers where the results depend on the azimuth of observations. If in addition the interval is anisotropic, the velocity obtained by straightforward application of the algorithm may be grossly in error.

One may ask how much the situation has improved since the introduction of new techniques for velocity estimation, as for example the slant stack method? Determination of interval velocities consists of separating the effects of overburden from the effect of the layer itself. While this separation in the distance-time domain is only approximately possible, the separation after a slant-stack transformation in the "ray parameter— intercept time" domain is strictly valid. However, most of the cautionary remarks are still valid and the basic concept of the method breaks down for dipping layers and any kind of lateral velocity gradients.

Estimation of Acoustic Impedance Sections from Reflection Data

Today the estimation of acoustic impedance from reflection data is one of the most important seismic tools for the identification and delineation of HC reservoirs. Field examples published by different companies confirm the successful application of this method. The example in Figure 9, taken from an advertisement of a geophysical contractor, shows the pseudo velocity section from an offshore prospect in a Tertiary sand/shale environment. The estimated impedance section is converted to a synthetic velocity section with the assumption of a functional relationship between velocity and density. We know that the acoustic impedance, or as shown here the P-wave interval velocity is low for high porosity sands, especially if the porefiller is gas.

Low velocities, coded by blue and light colours, identify the areas of HC interest in the lower part of the section. Two potential reservoirs which are confirmed by the results of the well can be seen at approximately 1.45 sec and 1.75 sec in the centre of the section, extending to the fault which can be seen between SP 229 and SP 256.

Again the validity of the estimated impedance results depends critically on some assumptions:

- good data quality,
- zero phase seismic signals,

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- suppression of multiples,
- broadband seismic data,
- flat reflectors and vertical incident.

The importance of wavelet processing and zero phase transformation is shown in Figure 10, where the results of seismic impedance estimations using the original seismic trace (left) and after zero phase transformation of the seismic trace (right) are compared with the impedance trace as determined from sonic and borehole density logs (Marschall, 1982). Only the results after zero phase transformation correlate with the well results. It is evident that zero phase transformation is a necessary prerequisite for reliable estimations. However, as wavelet processing is a fairly standard technique today, this is in principle no restriction. Much more severe is the need of broadband seismograms with frequency content greater than 125 Hz, depending on the geological situation and the required resolution. Figure 11 gives an impression of the limited resolution of seismic impedance estimations as shown in trace C in comparison to the sonic log shown in trace D.

For reservoir interpretation of seismic impedance sections one not only has to keep in mind the limitation in seismic resolution, but one has to answer the question of whether the bandwidth of the seismic lines enables a detailed reservoir interpretation. The resolution test can be done from a synthetic seismogram using the actual seismic signal and computing the pseudo log to see, if one can still identify the given reservoir problem.

The assumptions of the flat reflectors and vertical incident are at present generally disregarded. Efforts are under way to estimate the reflection coefficients for laterally curved boundaries using a method which is based on true amplitude migration.

For the use of seismic impedance sections in reservoir prediction the central question, besides this of the resolution is related to the allowance of the lateral extension of the impedance estimation away from the well location where the pseudo log is calibrated. Errors in impedance estimations are small as long as the geology differs not too much from the vertical homogeneous model and from the assumption of sharp discontinuities at the layer boundaries. However, without further well control we are in general unable to check the lateral validity of the assumptions as well as to define the spatial limits of reliable estimations. However, again, model calculations using well information are often quite helpful to decide if one can expect, for the given geological situation, large or small errors in the estimated impedance sections.

Seismogram Inversion

Great efforts are presently undertaken in the field of direct seismogram inversion, which means the direct extraction of the subsurface model from seismic data without any intermediate products such as stacked sections.

The main advantages in comparison to the present techniques of velocity and impedance extraction are the use of the whole data information of seismic records including multiples and less restrictive model assumptions.



Fig. 10. Pseudo Impedance Logs computed from the Original Seismic Trace (A), after Zero Phase Transformation of the Seismic Trace (B) and compared with the Actual Acoustic Impedance Log as measured at the Well Location (after Marshall, 1982).



Fig. 11. Seismogram Resolution: Comparison of an unfiltered seismic trace (A), deconvolved trace (B), pseudo impedance log (C) and Sonic log (D).

Even if progress has been made in the field of one dimensional trace inversion, direct inversion methods are, at the present time, hardly practical or successful. Seismogram inversion is a field of future research and development, from which one can expect further support for reservoir evaluation.

PREDICTION OF PETROPHYSICAL PARAMETERS FROM PHYSICAL PARAMETERS

Until now we have only discussed the problems in estimating physical parameters from seismic data. In principle, we do not explore for seismic velocity or impedance, but for materials that fill the pore space. The seismic parameters, traveltime and amplitude, of a fluid saturated porous rock depend on the saturating fluids, the porosity, the pore spectrum, the distribution of the fluids over the pore shapes and on the properties of the solid. The forward problem—to determine the seismic parameters from the information about the constituents of the compound—is always solvable, but the reverse problem—to determine the constituents' parameters from the seismic observations—is solvable only if sufficient information is on hand concerning the other parameters. Such inversion is for example possible if the material filling the pores

is the only quantity that varies, while all other relevant parameters are constant and known. In most of the cases, however, we don't have the necessary information to solve the inverse problem.

Therefore, equations which described the velocity of elastic waves of a composite medium on the properties of the constituents like the Gassman-Biot; Geertsma- or Brown/Korringa equation are used primarily for forward modelling (Gassmann, 1951; Biot, 1956; Geertsma and Smit, 1961; Brown and Korringa, 1975). The main purpose for their application is to check the influence of the different parameters on the seimic response, to assess which effects are most probably responsible for the changes of the physical parameters and to check the reliability of the interpretation.

Some cautionary remarks are necessary regarding quantitative determinations of petrophysical parameters from seismic velocities as for example the porosity. Even if in a given formation it is generally reasonably to assume that the velocity changes are mainly due to variations in porosity, lithology and fluid content, porosity estimations from seismic data are often far more an art than a reliable interpretation of seismic measurements. This is especially true in areas with complex lithology, characterized for example by multiple porosity types and thin porous layers. The lithology is too oversimplified by the seismic method to be usefully studied in its quantitative aspects. Due to the limited seismic resolution and the multi-parameter dependency of the velocities, porosity estimations from seismic interval velocities are restricted to areas with good well control and simple geological situations.

INTERACTIVE MODELLING IN RESERVOIR PREDICTION

Modelling experiments, with a stepwise change of the velocities and densities as measured at a well location have been most successful in HC prediction in deltaic areas with sufficient well control.

Interactive modelling has been quite helpful to correlate between wells and to check the lateral extent of the reservoirs (Neidell, 1980).

A simple example is shown in Figure 12 where the updip extension of a HCreservoir, found at the well location and marked in yellow, is predicted by forward modelling using log results of the well for the initial model. The comparison of modelling results with the seismic data indicates the pinchout of the sands within the shown window.

Only two of the results were shown in trace B and trace C for the models without the reservoir sands and without the green marked overlying shales.

Critique on interactive modelling is based on the fact that a good knowledge of the subsurface is required and the application of the procedures is restricted to areas where the superposition of reflection coefficients is well understood.

In the vicinity of a well these conditions are fulfilled and gross variations in lithology and fluid contact can be inferred by interactive modelling and data fitting as long as the seismic method is not beyond its limits of resolution.

- Fig. 12. Prediction of Reservoir Extension by Modelling
- Trace A = Synthetic Seismogram at the Well Location

 \mathbf{X}

- Trace B = Synthetic Seismogram without HC Reservoir Sands (Horizon Yellow)
- Trace C = Synthetic Seismogram without overlying shales (Horizon Green).

SUMMARY

Inspite of considerable improvements in Exploration Seismics during the last decade, the prediction of HC reservoirs is only solvable to a certain degree.

The absolute limits for the extraction of physical parameters from seismic data are given by the filter effect of the earth. Most restrictive for the estimation of the physical parameters is the limited seismic resolution in comparison to the requirements. One has to keep in mind that for reservoirs which are thin in comparison to the seismic wavelength, the extracted physical parameters represent only average values of a whole sequence of layers and lateral variations of the target are hard to identify. The absolute interpretation of seismically derived interval velocities and acoustic impedances in terms of lithology, porosity and porefiller is only possible for areas with dense well control.

Due to natural limitations of the resolution of seismic surface measurements, I believe that for field development and reservoir prediction in future seismic field techniques will be more and more orientated closer to the target and will include Seismic Vertical Profiling using P- and S-waves and even crosshole techniques.

Finally, I feel a little apologetic towards those companies whose work I have failed to mention. Even the examples taken from advertisements of several companies are selected quite randomly and may not represent their latest developments or the stage of development among the different companies.

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