S-WAVE VELOCITY AND POISSON'S RATIO FROM SHEAR WAVES OBSERVED IN NORMAL P-WAVE DATA IN AN OFFSHORE BASIN

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ABSTRACT

Normal seismic reflection records contain energy other than compressional waves (P-waves). This energy is treated as nuisance, and serious attempts are made to attenuate it in the field and in processing. However, if individual components of this energy -- particularly shear-wave (S-wave) components -- were present consistently, this would provide crucial information regarding the porefluid and lithology of the medium.

This study shows that S-waves are present in a consistent manner on a particular set of data recorded in an offshore basin. S-waves originate and convert back into P-waves at the sea floor. Continuous velocity analysis was used to compute P- and S-wave velocities from common midpoint gathers and derive a stacked S-wave section. The S-wave section shows several reflections which are equivalent to the P-wave section. Close examination of the two sections suggests that a bright spot on the P-wave section is probably due to a dry reservoir rather than a limestone stringer even though the S-wave section is noisy in this zone. Poisson's ratios can be computed for several zones from time intervals on the P- and S-wave section but not from interval velocities derived from continuous velocity analyses.

INTRODUCTION

Shear-wave (S-wave) velocity in combination with compressional-wave (P-wave) velocity provides additional information about lithology and porefluid of the medium (Tatham, 1982), and a comparison of two stacked sections can be used to detect gas reservoirs (Ensley, 1984). However, direct S-wave recording is not possible in offshore areas. On land, it is expensive and the problems associated with S-wave source generation and with processing of the data are considerable, though not insurmountable. Amplitude-vs-offset analysis (Ostrander, 1984) has been suggested as an economic alternative although the approach is likely to be effective for translucent beds only when the signal-to-noise ratio on prestack data is exceptionally good (Jain, 1987).

An analysis of stations 540 to 710 from an offshore survey shows that very low-velocity and very low-frequency events are present on field records. These events correspond to shear waves originating very close to the surface and travelling to and from the reflector with the velocities corresponding to those of the shear waves. Assuming that these events are indeed S-waves which originated from conversion of P-waves at or near the sea floor and converted back into P-waves at the same level, I compute S-wave velocities and Poisson's ratios, generate the S-wave stacked section, and briefly refer to their significance in the interpretation of data. The general consistency of these results supports the basic thesis of this paper that events have been recorded on these offshore data which have travelled as S-waves below the water.

Description of data

The seismic profile discussed here was recorded in 1984 for 6.0 s using TI DFS V, a 50 000-cm³ tuned air-gun array at a depth of 7 m, using an air pressure of 14 000 kPa. Cable depth was 12 m; pop interval and group interval were 25 m; receiver spread was from 209 to 3159 m from the source; and coverage was 60-fold. The signal-to-noise ratio in the data was good both before and after stack. The water depth was consistent at 90 m. The water bottom was soft and the dereverberation was successfully achieved by predictive deconvolution. The P-wave stack section with a preliminary interpretation is shown in Figure 1.

ORIGINS OF S-WAVES AND DISCRIMINATION FROM MULTIPLES

At receivers close to the source, the incidence at the reflectors is near normal and conversion of P-waves into S-waves is negligible. However, at larger offsets and higher incidence angles, the magnitude of S-wave energy in the lower layer can be considerable. Tooley et al. (1965) showed that at a liquid/solid interface, "we have a very efficient generator of S-waves" where 25 to 95 per-

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cent of incident energy is converted into shear waves at incidence angles as low as 20° (Figure 2). As shown in the inset of this figure, converted S-waves are nearer to the vertical than the P-waves incident on the water bottom. Therefore, the "depth of penetration" of S-wave energy is large even though the refracted P-wave energy at this incidence may approach critical incidence.

The velocity of S-waves is approximately half of the velocity of P-waves. Therefore, in the case of normal incidence, S-wave reflections occur at approximately twice the traveltime of P-wave reflections, which is approximately where the simple multiples are expected. Therefore, it is crucial to be able to discriminate between them. The S-waves can be identified by their lower stacking (rms) velocity and lower frequency (Anno, 1987; Garotta, 1987) which are expected to be approximately half of those of the simple multiples at corresponding times. S-wave stacking velocities used in this study were close to the lower end of the expected range (Figure 3) and were lower than the velocity of water above two sec-

![Fig. 1. Stacked P-wave section, stations 540 to 710 with an elementary interpretation.](image-url)
ons on the stacked section. Below two seconds they were generally 20 to 40 percent lower than the expected stacking velocity of the simple multiples, which is the same as that of the primaries causing them but at twice the traveltime of the primaries. The water-bottom multiples from deeper reflections are not expected to be significant on the S-wave stack because their stacking velocities are even higher than those of simple multiples. There was no evidence of near-surface reverberations on the prestack data. However, as a precaution, the first 25 traces in each CMP group (offset 209 to 1409 m), where the moveout contrast between S-waves and multiples is small, were omitted from S-wave velocity computations and stacking. This also maximized the expected S-wave/P-wave energy ratio in the data being analyzed.

CONVERTED S-WAVES

CMP gathers

Figure 4 shows two typical CMP gathers for stations 540 and 604. The predominant frequency band of energy on these traces is 10 to 40 Hz. The expected spectrum of any S-wave energy would be 5 to 20 Hz (Anno, 1987; Garotta, 1987). Therefore, in order to enhance any S-wave energy which may be present, relative to P-wave reflections, these records were filtered with a 0/5-15/20 Hz trapezoidal bandpass filter. Figure 5 shows the traces in Figure 4 after application of this filter. The curved overlays correspond to normal moveout for velocity 0.55 times the velocity used in stacking the data in Figure 1. The correspondence of some events with overlays shows that there is a high probability of reflections corresponding to S-wave velocities having been recorded on the farther traces of these two gathers. Figure 6 shows these gathers after normal moveout correction with velocities computed for S-waves and described later. In Figure 7, the gathers have been filtered with a 7-trace, 72-ms two-dimensional filter (Jain, 1979) to attenuate overcorrected P-wave reflections. While some of the events identified on the farthest traces above 2.0 s may be questionable, Figures 6 and 7 show sufficient evidence of events which line up and sometimes show small residual normal moveout.

S-wave stack

The CMP gathers were corrected for S-wave velocities computed from continuous velocity analysis (to be described in the next section) and traces 26 to 60 were stacked. Figure 8 shows this stacked S-wave section. Note that the data have been filtered with a 0/5-15/20 Hz bandpass filter and displayed at an appropriate time scale for easy comparison.

Several very low-velocity events are present which are probably the aliased remnants of overcorrected P-wave reflections. To attenuate these events, a two-dimensional filter, similar to the one used in Figure 7, was applied to the stacked traces in Figure 8. Also, the data below 3.0 s was scaled up (Figure 9). The reflections and faults picked from the P-wave section (Figure 1) are also shown on the S-wave sections. While the correlation on the S-wave sections above 2.0 s is sometimes questionable, the general agreement of P-section interpretation with S-wave data is remarkable.

Two particular dissimilarities between P- and S-wave sections need to be mentioned. The bright spot between
Fig. 4. Common-midpoint gathers for stations 540 and 604.
Fig. 5. CMP gathers for stations 540 and 604 after a low-pass filter, passband 0/5-15/20 Hz. Normal moveout overlays correspond to expected S-wave velocities.
Fig. 6. CMP gathers after normal moveout correction with S-wave velocities. Although overcorrected P-wave reflections predominate, several lineups can be noticed on farther traces.
Fig. 7. CMP gathers in Figure 5 after two-dimensional filtering to attenuate overcorrected P-wave reflections. Several lineups corresponding to probable S-wave events have been identified.
stations 590 and 640 at 0.85 to 0.80 s on the $P$-wave section does not have a corresponding event on the $S$-wave section. Although allowance has to be made for poor quality of $S$-wave stack in this zone, this increases the possibility that the amplitude anomaly is due to a gas-filled sand deposit rather than due to one of the limestone stringers which are known to occur at that depth. The dipping event on the $S$-wave section between 2.6 and 2.8 s at stations 605 to 637 is not observed on the $P$-wave section. This feature has not been analyzed in detail. It is unlikely to be a diffraction because the $P$-wave stack does not show it. One possible cause is a sand body (thickness 80 ms, $P$-wave time), which could give rise to this feature if the Poisson's ratio of sand declines from 0.4 (very unconsolidated) at station 605 to 0.25 (consolidated) at station 630.

Nine picked reflections in the $P$- and $S$-wave sections were used to compute Poisson's ratios from time intervals of corresponding events (Figure 10). These values are probably no more than crude approximations of the true values but they do agree with the expected lithology and structure.

$P$- and $S$-Wave Velocities and Poisson's Ratio

Continuous velocity analysis

Root-mean-square (rms) and interval velocities were computed from each uncorrected CMP gather. For $P$-
wave velocities, all sixty traces were used after application of a bandpass filter of 5/10-60/70 Hz. For S-wave velocities, the 25 traces nearest the shot were omitted and the remaining traces were filtered with a bandpass filter of 0/5-15/20 Hz. The details of the computing process are not critical to velocity estimates. Very briefly, the best rms velocities are computed for each CMP gather independently by picking events within a specified range known from nearby sonic logs or from previous analysis, as was the case in this study. Rms velocities were converted into interval velocities using the equation derived by Dix (1955). The resulting interval velocities showed large and unrealistic fluctuations from trace to trace for both P- and S-velocities. These fluctuations were largely attenuated by applying a two-dimensional filter (39 traces, 44 ms) designed to pass wavelengths greater than 41 traces (2 000 m) and frequencies less than 50 Hz (Jain, 1979).

**P-wave velocities**

P-wave interval velocities computed for the section are shown in Figure 11. The section in Figure 1 is overlain on a colour display of a velocity plot. There is a general agreement between velocity features and seismic overlay.
Fig. 10. Poisson's ratio computed from transit times in the sections of Figures 1 and 9.
Fig. 11. P-wave interval velocities computed from CMP gathers after long-wavelength low-frequency two-dimensional filtering.
Fig. 12. S-wave interval velocity from farthest 35 traces. Note the time scale has been changed to match approximately with Figure 11.
Fig. 13. S-wave interval velocity in Figure 12 plotted at P-wave times. Note 300-ms discrepancy in character vis-à-vis Figure 11.
Fig. 14. Poisson’s ratio for $P$- and $S$-wave velocities in Figures 11 and 13.
However, the bright spots are not identified by interval velocities, probably because the zones causing the bright spots are not thick enough to be identified via the rms velocities of significantly larger intervals.

Two blue patches in the purple zones at 2.35 s from stations 560 to 580 and 590 to 610 in Figure 11 are of significant interest because they indicate the presence of porous zones in the carbonate formation.

**S-wave velocities**

S-wave interval velocities were computed from far traces of CMP gathers after a low bandpass filter of 0/5-15/20 Hz. The base S-wave velocity function was half of the stacking velocity at twice the P-wave traveltine. Possible error in rms velocity was assumed to be 20 percent which covers all practical values of Poisson’s ratio for the medium. The interval velocities computed from traces 26 to 60 in each CMP group (1459-3159 m) are shown in Figure 12. In order to facilitate the comparison of various figures, the time of the S-wave velocity section was adjusted to correspond to P-wave times by converting S-wave times to depth and then converting these depths to time using P-wave velocity in Figure 11.

S-wave interval velocities for P-wave times are shown in Figure 13. A comparison of Figures 11 and 13 shows that S-wave velocities are 300 ms higher in the section than the corresponding P-wave velocities. This discrepancy is most probably due to a combination of curved raypaths and errors in very shallow velocities. The P-wave seismic section overlay has been adjusted for this discrepancy. While the agreement in S-wave velocities and the P-wave section is very good above 1.8 s (P-wave time), the general agreement in the deeper section is still acceptable.

The two sets of interval velocities in Figures 11 and 13 were used to compute Poisson’s ratio at each data sample (Figure 14). S-wave velocities were adjusted for the discrepancy referred to above before making this computation. Although the horizontal and vertical variations match the P-wave section, Poisson’s ratios range from 0.2 to 0.5, too high by up to 30 percent. Moreover, these values are in substantial disagreement with those in Figure 10. A small error in either primary or shear-wave velocities can cause a relatively large error in Poisson’s ratio; e.g., ±100 m/s error in either velocity may change the ratio from 0.29 to 0.34. In this case, estimated shear-wave interval velocities are probably too low by about 10 percent.

The process above was repeated with traces 37 to 60 (2009-3159 m) and the same base velocities. The computed velocities were very similar to those in Figure 13. A conventional velocity analysis which stacks the traces with different velocities and picks the one that gives the most energy was used with the same parameters; essentially the same velocity distribution was obtained. When base velocities were increased by about 20 percent, somewhat higher S-wave velocities were obtained. However, the stack with these velocities was quite unsatisfactory compared to that from velocities in Figure 13 and shown in Figure 8. Taner and Koehler (1969) have discussed an implied approximation for large offsets in Dix’s equation. Velocities computed using three terms in their general normal moveout equation were up to 5 percent lower than those in Figure 13, while Poisson’s ratios were even higher than in Figure 14. Therefore, I conclude that, with these data, continuous velocity analysis of CMP data with a large range of possible S-wave velocities and other parameters provides reliable rms velocity values for stacking. (This in itself can be considered as support for the hypothesis of the existence of useful S-wave energy.) However, the interval velocities computed from normal moveout analysis without accounting for anisotropy are not accurate enough for computation of useful Poisson’s ratios. As shown in Figure 10, the comparison of P-wave and S-wave sections provided more reasonable estimates of in-situ Poisson’s ratios over thick sections for estimating lithology in this virgin area. Velocity estimation techniques must be improved (particularly for S-waves) before it is possible to estimate the Poisson’s ratios over relatively thin zones.

An analysis of data from another offshore area gave similar results and confirmed the general conclusions of this study.

**CONCLUSION**

There is a high probability that consistent S-wave energy is present in a set of offshore data. This energy originates on conversion of some of the P-wave energy into S-waves at the sea floor, as predicted by Tooley et al. (1965). These converted waves travelled downwards and back as S-waves and were converted back into P-waves at the sea floor. The S-wave section computed by stacking farther CMP traces shows general agreement with structure interpreted on the P-wave stack and the Poisson’s ratios can be computed from corresponding time intervals. A prominent bright spot on the P-wave section is absent on the S-wave section indicating that the amplitude anomaly is more likely due to a dry reservoir than a limestone stringer. The continuous velocity analysis gave good stacking velocities for the S-waves, but the interval velocities were not accurate enough to compute reliable Poisson’s ratios.

**REFERENCES**


S-WAVE VELOCITY AND POISSON'S RATIO FROM SHEAR WAVES OBSERVED


