EXPLORING WITH SH-WAVES†

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ABSTRACT

Shear waves propagating with a displacement vector parallel to the stratification, or SH-waves, have interesting properties:

1) Their velocity is a function of rigidity, not of compressibility and rigidity as in P-waves. Thus, the ratio Vs/Vp can be used for mapping facies changes.

2) Resolution is frequently superior because:

— the lower velocities facilitate the detection of small structures;

— sand/shales contacts are more easily detected;

— the laws of propagation in layered media are simpler than for P- and SV-waves; in particular, there are no mode conversions.

3) Fluids in a solid matrix do not directly influence the propagation of SH-waves. Thus, SH-waves can help verify the nature of P-wave bright spots. A SH-wave bright spot is necessarily caused by the matrix, not gas.

SH-wave sources presently in use are explosives (detonating cord, dynamite) fired near trenches or cavities, horizontal vibrators and lateral weight dropping. Recording arrays are similar to those used for P-waves except that geophones have a horizontal axis; consequently noise caused by the wind is stronger. Processing and interpretation methods are similar to those followed in the case of P-waves although static corrections may be more involved. Examples of combined interpretations of P- and SH-wave data show that difficulties particular to exploration with SH-waves should not prevent explorationists from considering their use.

INTRODUCTION

Simeon Denis Poisson (1781-1840) investigating the propagation of acoustic waves through elastic solids found that at large enough distances from the source he could distinguish between two types of waves. The higher velocity wave appeared to be longitudinal, the lower velocity one appeared to be transverse. It was George Gabriel Stokes (1819-1903) who showed that the body waves discovered by Poisson correspond respectively to irrotational dilatation and to equivoluminal distortion. Stokes also defined the shear or rigidity modulus. By 1845 the foundations of the mathematical theory of acoustic wave propagation had been laid out and experimental seismology became a field of activity for several scientists. Until 1921 it was restricted to the study of natural earthquakes.

Since 1921 the story of the spectacular development of exploration seismic has been essentially the story of P-wave exploration techniques, an obvious reason being that P-waves arrive first and are more easily generated with explosive charges. As a matter of fact, until the mid-sixties it seems that most researchers limited their experiments to tests of shear wave sources.

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A SH reflection line was presented for the first time at a SEG Annual Meeting in 1966 and published in *Geophysics* in April 1968 (see "Shear Wave Recording Using Continuous Signal Methods," by Erickson, Miller and Waters).

Since, SH-waves profiles have been recorded in various countries. Several crews work exclusively with SH-waves in the Soviet Union. A number of sites have been surveyed in Western Europe and North America generally with both SH- and P-waves.

At this still relatively early stage of the introduction of SH-waves among seismic exploration techniques many geophysicists might ask: Why use SH-waves in exploration seismic? How can we generate and record SH-waves? Did we reach a stage where results are of a sufficient quality to be used profitably in interpretation work? These are the questions the present paper endeavors to answer in a succinct manner.

WHY USE SHEAR WAVES?

The following equations express the velocities of P- and S-waves in a homogeneous isotropic medium as functions of two elastic constants and the density:

$$V_p = \left(\frac{k + \frac{4}{3}\mu}{\rho}\right)^{\frac{1}{2}}, \qquad V_s = \left(\frac{\mu}{\rho}\right)^{\frac{1}{2}};$$

Vs, Vp: velocities of P- and S-waves in m/s;
k: incompressibility or bulk modulus in N/m^2;
μ: rigidity modulus (or Shear modulus) in N/m^2;
ρ: density in kg/m^3.

Thus, $V_s/V_p = \left(\frac{\mu}{k + \frac{4}{3}\mu}\right)^{\frac{1}{2}}$.

k is about 2.5 to 3.0μ, thus Vs/Vp is about 0.5 for most geological formations. It generally ranges from 0.3 to 0.7.

Considering these simple formulas, seven different kinds of improvements in the knowledge of the subsurface may be expected from the combined uses of SH-waves and P-waves in exploration:

1) The ratio Vs/Vp is affected by changes in the lithology: when calculated within a given interval between two reflections it can be expected to give indications about lateral facies changes. For example, an increase in the proportion of carbonates in a shaly series causes Vs/Vp to rise because carbonate formations are more rigid.

   Figure 1 illustrates statistical distributions of Vs and Vp versus density. The clustering of data points near the average curves is remarkable. The increase with density of both velocities shows the influence of cementation on density and the rigidity and bulk moduli. The curve Vs/Vp is steeper within the domain corresponding to sedimentary rocks, thus confirming the influence of facies on Vs/Vp.

   The curve plotted in the upper part of the figure corresponds to Poisson's ratio which is a simple function of Vs/Vp. Poisson's ratio is the ratio of transverse strain over longitudinal strain in the case of an elastic solid under stress. For rocks it ranges from 0.1 - 0.25 for very rigid formations like some igneous rocks or well-cemented sandstones, to 0.45 - 0.49 for some shales and muds. Either Vs/Vp or Poisson's ratio may be used as indicator of facies change.

2) Fluids in a solid matrix have little influence on Vs. On the contrary, the presence of a compressible fluid in a porous matrix lowers Vp. Thus, a SH-wave survey can help ascertain the cause of P-wave bright spots. A SH bright spot is necessarily caused by the matrix, not gas.

3) Jointing and fracturing can cause a considerable decrease of the macroscopic rigidity modulus. Thus shear waves can be expected to be the best surface geophysical method available for the detection of reservoirs due to fracturing. This is supported by borehole measurements (Morris, Grine and Arkfeld, 1964) showing that Vs decreases relatively more than Vp when fracturing is present.

4) SH-waves are much more strongly affected by the anisotropy of layered media than P-waves. Anisotropy is affected by the proportion of clay minerals in shales or sands and by

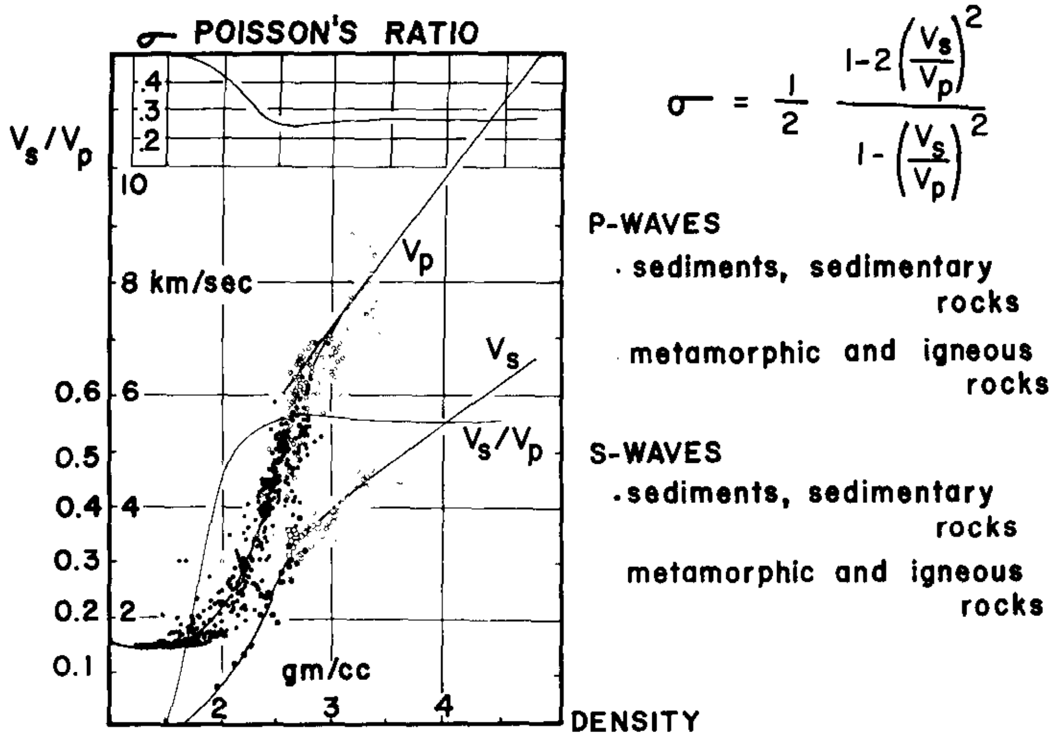

Fig. 1. Velocity versus density for P- and S-waves in all types of rocks. (After M. Dobrin from data assembled by J.E. Nafe, curve Vs/Vp added.)

jointing in limestones and sandstones (Garotta et al, 1977).

5) A better resolution can be expected from SH-waves than from P-waves. Because Vs is generally about half of Vp, SH-waves are better adapted to the study of small amplitude structures. Though the content of high frequency energy is lower than in the case of P-waves, the wavelength is shorter for SH-waves because a significant amount of SH-wave energy corresponds to frequencies of the upper half of the P-wave spectrum.

6) Horizontally polarized S-waves, or SH-waves, are generated for exploration purposes. In a horizontally layered medium, SH-waves are not affected by mode conversion as is the case for P- or SV-waves. Thus, SH-wave sections are generally simpler than P-wave sections.

7) The fact that SH-waves are polarized may be used for dip determinations in some structural studies. An anomalous dip in a layered series may be expected to cause a reduction of the reflection amplitude.

Generating and Recording SH-Waves

Two types of sources have been used successfully in the field: explosive sources and mechanical surface sources.

The explosion of a spherical explosive charge is a center of expansion. Theoretically, in a solid homogeneous isotropic medium, a center of expansion radiates only P-waves (i.e., the rotational component of the displacement vector vanishes). Actually it seems that because completely homogeneous grounds do not exist, most underground explosions radiate some energy as shear waves.

Geyer and Martner (1969) report that "the SH motion is in some way correlatable with a marked velocity contrast". Travel time curves obtained in the Edwards limestone show that time intercepts of the P and SH curves are the same. Thus, both motions originate near the shot point and the explosion may be considered as their common source.

Hazelbroek (1966) considered the theoretical case of a finite line source in a homogeneous medium and found that it would generate shear waves and the more so if the Poisson ratio is higher. This is an interesting result because many near surface formations have relatively large Poisson ratios.

How can we increase the fraction of energy transmitted as SH-waves?

If on one side of a buried charge a long cave or trench is created, pressure waves caused by the explosion are absorbed to a certain point by the cave or trench. The explosion is not a spherical center of expansion anymore and horizontal shear waves are created by the unbalanced pressure on the side opposite to the cave or trench. If the trench or line of caves is located along the plane of symmetry of two line sources or two rows of point charges, the corresponding SH-wave signals received at a given station located on the trend have mirror image polarities, whereas the polarity of the P-wave signals is not reversed.

Figures 2 and 3 illustrate the principle* of the generation of SH-waves with line sources in trenches (detonating cord) or rows of point charges (dynamite) in shot holes. The use of detonating cord is by far more practical, the use of shot holes is of interest when the trench dug for the detonating cord would remain within a loose sandy soil.

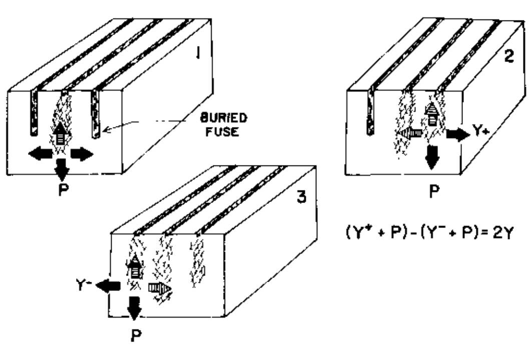

Fig. 2. Generating SH-waves with Detonating Fuse: The Syslap* Method

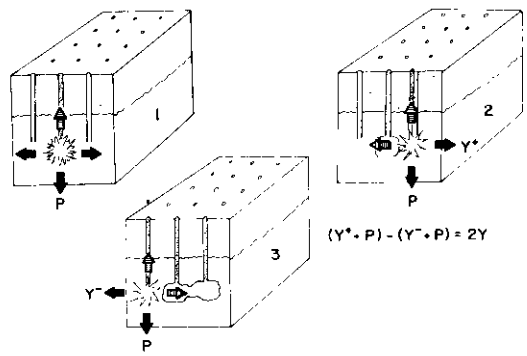

Fig. 3. An Application of the Syslap* Method: Generating SH-Waves with dynamite where Loose Overburden Prevents the Use of Detonating Fuse or Vibrators

When one of the two records obtained by firing the charges on both sides of the central trench or line of caves is subtracted from the other, the SH signals add up while the P

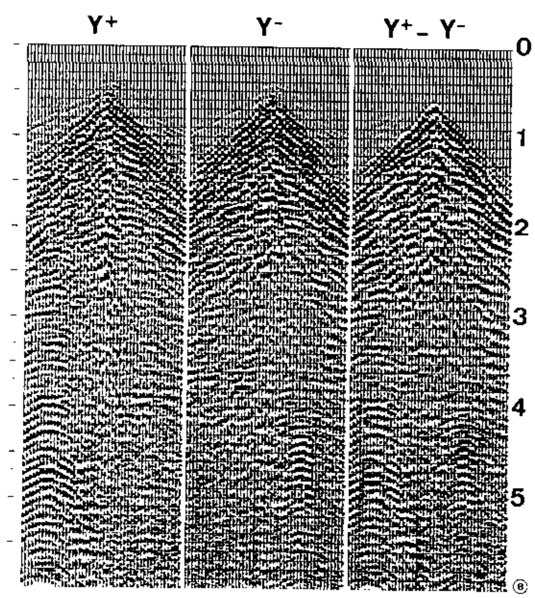

Fig. 4. S-Waves: Detonating Fuse

*The SYSLAP method: Service and Trademark of CGG

2-3: Portlandian: well-cemented limestone (160 m);

3-4: Kimmeridgian: limy shales (150 m);

4-5: Lusitanian: limestone (270 m).

The SH-wave section is shown on Figure 7. It was obtained with a lateral weight dropping system or MARTHOR; 12 drops were stacked. The surface formation is sandy clayey soil. The corresponding P-wave section is presented on Figure 8. The source consisted of 50 meters of 200 grain per foot detonating cord in a single furrow 2.6 feet deep. In both cases the CMP coverage was 2400%. The SIGNET* deconvolution procedure using the near field source signature was applied to both sections.

Both sections are of a good quality. The SH section is simpler in the upper part corresponding to two-way times of less than 800 ms on the P section. The use of a time scale divided by two for the SH-waves roughly reduces the comparison of the two sections to a comparison of depth sections. The dominant wavelengths are shorter in the case of the SH section.

Figures 9 and 10 show the results of velocity analyses on two different horizons for both P- and SH-waves. The definition of velocities is better for the P-waves but the presence of peg-leg multiples is noticeable while SH results are free of them.

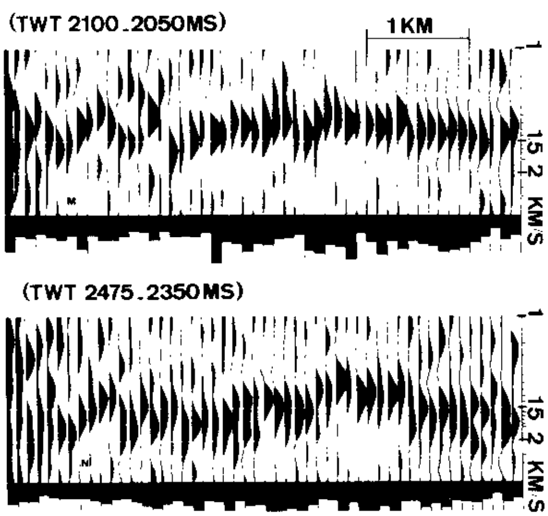

Fig. 9. S-Waves Velocity Horizons

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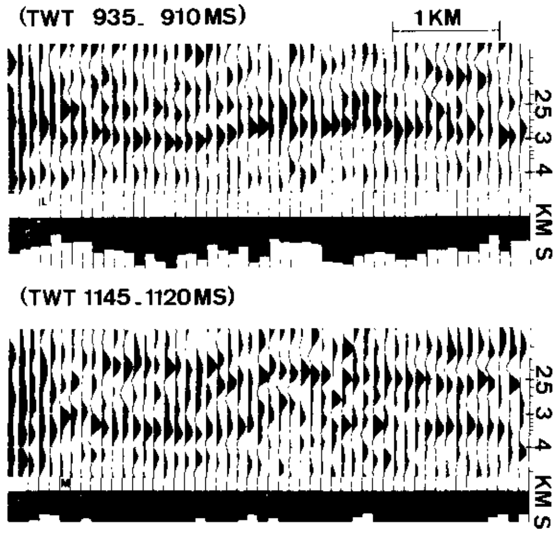

Fig. 10. P-Waves Velocity Horizons

Correlations are displayed in Figure 11. The SH time scale has been locally stretched or compressed in order to obtain equal ordinates for corresponding events.

Figure 12 shows the γ_T = Tp/Ts = Vs/Vp ratios for the four stratigraphic intervals defined earlier. The ratios are in agreement with known lithology (Molotova and Vassil'ev, 1960). The sections being of a good quality, the accuracy of the γ_T ratios may be considered as better than 5% for the thinnest interval although it should be remembered that the correlations of the P and SH events result from an interpretative work.

1-2: Lower Cretaceous: Vs/Vp rises from 0.50 to about 0.55 at the northern end of the line. The Lower Cretaceous is actually the most interesting stratigraphic interval in the area. Its lower part, the Cenomanian shales and sands, overlies an erosion surface at the top of the Portlandian. Some sandstone bodies interpreted as sand bars parallel to ancient shorlines contain oil about 30 miles east of the seismic line. Other sandstone bodies about 20 meters higher, thought to be fills of an ancient hydrographic network, also contain oil in the same Chateaurenard field. It might thus

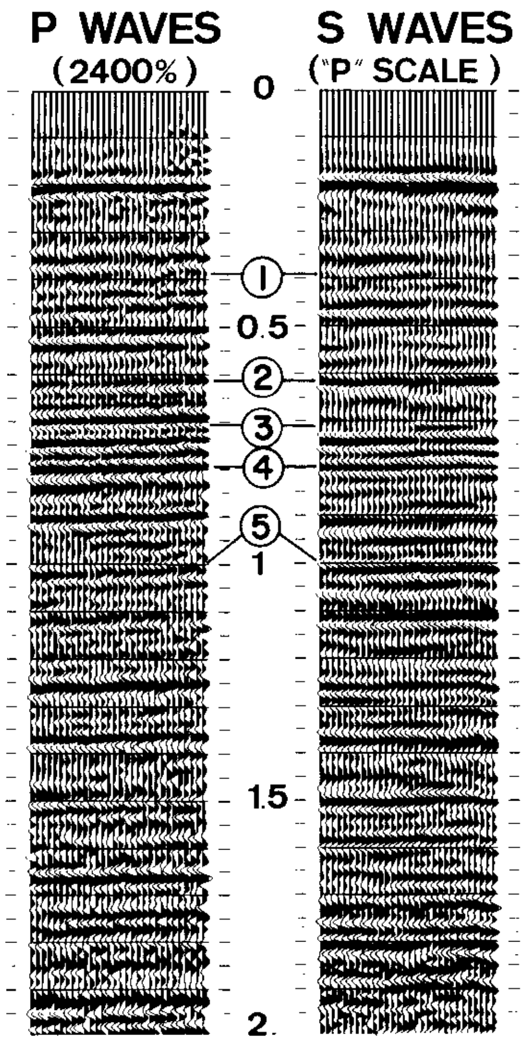

Fig. 11. P-Waves and S-Waves Correlations

be thought that it would be interesting to detect lateral variations in the proportion of sandstones in the Lower Cretaceous. The higher values of Vs/Vp at the northern end could thus be of interest.

2-3: Portlandian: Vs/Vp is higher than 0.5 and reaches 0.6 in agreement with the nature of the well-cemented limestone. The relatively strong lateral variations might reflect the effect of karstic erosion at the top.

3-4: Kimmeridgian: Vs/Vp is definitely lower, ranging from 0.41 to 0.49 in good agreement with the shaly nature of the stratigraphic interval.

4-5: Lusitanian: Vs/Vp is almost constant ranging from 0.46 to 0.52. Thus Vs/Vp is on the average lower than in the case of the Portlandian. As a matter of fact, the Lusitanian limestone is not as well cemented as the Portlandian limestone.

The dots plotted on Figure 12 correspond to γ_V = Vs/Vp ratios calculated on the basis of the results of velocity analyses. It may be observed that they are generally higher than the ratios γ_T = Vs/Vp = Tp/Ts. Tp/Ts correspond to vertical raypaths while the RMS velocities determined through velocity analyses reflect the horizontal components of the raypaths. Thus the discrepancy between the two ratios, γ_V and γ_T, increases with anisotropy. As a matter of fact, it is found that anisotropy is much more important for SH-waves than for P-waves, Garotta et al (1977). In this particular case the differences between γ_T and γ_V are especially important in the case of the shaly Kimmeridgian. Shales are generally more anisotropic than limestones or sandstones.

The next three figures are documents resulting from a survey carried out in Oklahoma on the East Shelf of the Anadarko Basin. Surface formations are terrace deposits, loess and Permian red beds. For both

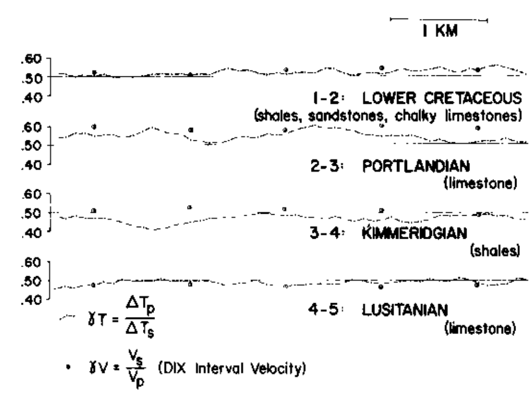

Fig. 12. γ Ratios

the SH- and the P-waves, the source was a 220 foot strand of 200 grain per foot detonating cord. The SYSLAP method was used (see Figure 2). The three strands were buried in furrows three feet apart. The array was the same for the SH- and the P-waves: symmetrical split spread, 48 traces, 220 feet between traces, 2400% coverage.

The lowest sedimentary horizons of interest are about 10,000 feet deep. The Permian and Pennsylvanian systems comprise shales, sandstones and limestones. The proportion of carbonate is higher in the Mississippian.

Figures 13 and 14 are respectively corresponding fragments of the SH and P final deconvolved sections. They are both of a good quality though events have more character on the P-wave section because the frequency band is broader. At the middle of the lower part of both figures a structure may be observed. It is interpreted as a porous dolomite body ("dolomite pod") within the Hunton more compact carbonates. The top of the structure is at 1800 ms on the P-wave section. The top of the Mississippian is at 1600 ms.

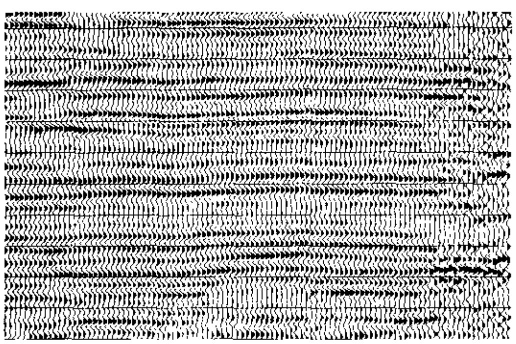
3.6
3.8

Fig. 13. SH-Wave Section: Feature Interpreted as a Dolomite Pod in the Hunton

Though these sections are not the results of preserved amplitude processing, a shadow effect is observed under the structure. It is actually much more pronounced on the SH section. It might appear abnormal to have a "dim spot" more pronounced on a SH section than on the corresponding P section. In the present case, it is considered that the SH "dim spot" is most probably due to the relatively reduced rigidity modulus of the dolomitic body. This is sustained by a decrease of the Vs/Vp ratio. The decrease of the rigidity modulus could be explained by the presence of numerous joints enlarged by dissolution phenomena which could have taken place during the pre-Woodford erosion.

Figure 15 illustrates correlations between lithology and the ratio Vs/Vp in the case of three stratigraphic intervals. A Permian interval comprising sandstones and anhydrite is characterized by an almost constant and relatively high Vs/Vp ratio of 0.60. A Missourian interval comprised of shales and sandstones is characterized by a lower and more variable Vs/Vp ratio ranging from 0.38

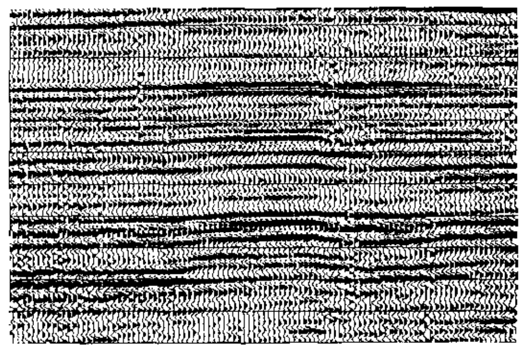
1.8
2.0

Fig. 14. P-Wave Section: Feature Interpreted as a Dolomite Pod in the Hunton

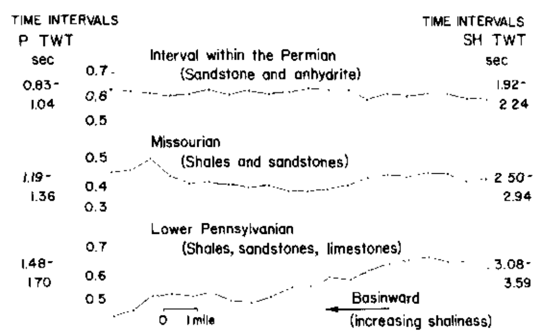

Fig. 15. East Shelf Anadarko Basin: Lithology and the Vs/Vp = Tp/Ts Ratios

to 0.50. A Lower Pennsylvanian interval comprised of shales, sandstones and limestones shows a Vs/Vp ratio decreasing almost regularly from about 0.63 to about 0.45 when going basinward from one end of the line to the other. This is interpreted as reflecting the basinward increasing shaliness of the stratigraphic interval.

CONCLUSIONS

Results obtained in various countries with different techniques since 1970 show that SH-wave reflection seismic is now past the early experimental stage. Results of a quality equivalent to the quality of normal P-wave data can be obtained with both explosive sources and surface mechanical sources.

The additional information brought by SH-wave surveys is particularly interesting when a stratigraphic interpretation is required. A wealth of information can actually be expected about the lithology, lateral facies changes, fracturing and jointing. SH-waves can also be a very useful diagnostic method when P-wave "bright spots" or "dim spots" are difficult to interpret.

Depending on local conditions, it might be somewhat more difficult to acquire and interpret SH-wave than P-wave data. Considering the additional information which might be obtained, these difficulties should not prevent explorationists from using SH-waves when local conditions are appropriate.

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