Present status and future directions of shear-wave seismology in exploration

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ABSTRACT

Shear-waves respond to a different combination of elastic constants, and density, than P-waves. The reflected P-wave however, is often the easier wave-type to generate, record, and process routinely, and has become the standard for imaging of subsurface structure. Including shear-wave data into our interpretations has led to discrimination of gas-related from non-hydrocarbon related reflection amplitude anomalies. Furthermore, combining time measurements of P- and S-wave data has led to estimation of lithology in the subsurface and estimation of fracture parameters from multicomponent VSP data. Recognition of the need to apply rotational corrections for the azimuthal anisotropy that pervades in many areas has led to consistent three-component recording. More recent developments have improved our capability to record and successfully process mode-converted data, particularly P-SV reflected data. Improvements in processing, including proper 'binning' and DMO correction of the asymmetric geometry associated with the P-SV reflection path is becoming routine. As new developments evolve, high-quality structural P-SV sections, simultaneous inversion of P-P and P-SV data for variations in P- and S-wave velocity, interpretation of P-P and P-SV reflection sections for Vp/Vs ratios in stratigraphic intervals, and inclusion of P-P and P-SV AVO analysis could lead to a fully integrated interpretation of structure, lithology, porosity and reduction in the risk of finding hydrocarbons.

INTRODUCTION

With the inclusion of shear-wave information into our conventional interpretations, industry practitioners have been teased by successes and near-successes of the techniques. Numerous controlled experiments have demonstrated the efficacy of shear-wave technology, but often with apparent limitations, and results have only moderately impressed many interpreters and exploration executives. As experience has evolved, the importance of anisotropy in many areas of the world and the additional potential of exploiting shear-wave anisotropy information for estimation of fracture parameters has been recognized. On the other hand, the perceived possibility of extracting similar lithologic information from P-wave AVO data has contributed to a waxing and waning of interest in the potential of direct shear-wave methods. Problems have included the expense of acquiring direct shear wave data, the damaging effects of massive mechanical shear-wave sources and the associated permitting problems, limitations in the resolution of direct shear-wave data. and the lack of availability of shear-wave recording capability. Successes have included controlled demonstrations of shear-wave techniques to discriminate between lignite-induced and gas-induced P-wave DHI amplitude anomalies (e.g. Ensley, 1985), the use of P-wave and S-wave data to estimate thickness of gas-reservoirs for cases with and without P-wave bright spots (e.g., Tatham and Krug, 1985, Tatham and McCormack, 1991). Other demonstrations have included documented mapping of lateral variations in subsurface lithology from P- and S-wave surface data (e.g., McCormack et al., 1984, Tatham, 1985), and estimation of fracture orientation form VSP (e.g., Winterstein and Meadows, 1991a,b) and surface (e.g. Martin and Davis, 1987; Mueller, 1991; Li *et al.*, 1993) data.

REVIEW

Pioneers in our industry have always recognized the presence of both shear-wave and compressional-wave energy as a fundamental part of seismic wave propagation. This was especially apparent during the 1950s as most laboratories of major companies in the industry embarked on fundamental observational studies of seismic wave propagation (e.g., Jolly, 1956; Press and Dobrin, 1956; White *et al.*, 1956). Essentially all of the reported experiments included both P-wave and S-wave observations as well as their relation to surface-wave propagation and "ground-roll." P-wave energy, the dominate type of wave generated by explosive sources, proved superior to S-wave energy in structurally mapping the subsurface. Thus, P-wave seismic wave propagation evolved into the standard seismic mapping method, and rightfully remains so today. Shear-waves, however, were recognized as important in defining ground-roll, and have even been reported in a few early exploration publications as potentially useful in isolated exploration settings. Shear waves were recognized as responding to different sets of elastic constants than P-waves, and thus respond to different elastic properties of the rocks than do P-waves.

In 1968, Conoco scientists (Cherry and Waters, 1968; Erickson *et al.*, 1968) published two significant papers on generating shear-waves with mechanical vibratory sources. They recognized the velocity ratio V_p/V_s, which is equivalent to the time ratio t_s/t_p calculated form the reflection time section, as a potentially useful quantity. In their paper, however, they did not discuss the direct application of V_p/V_s to lithology, as presented by Pickett (1963) or the potential response of V_p/V_s to the presence of gas, as discussed by Gardner and Harris (1968). They did observe interpretable S-wave data, however, and did map the ratio V_s/V_p (rather than V_p/V_s) from P- and S-wave reflection data between two wells and correlated the observed V_s/V_p variations to changes in the thickness of the Hunton limestone.

With some of these successes, Conoco proposed a relatively large group-shoot in about 1976. This led to the formation of the group of 13 major oil companies, operated by Conoco. The project included the construction of three large shear-wave vibrators, the identification of about 20 potential controlled test sites and the acquisition of both P- and S-wave data over most of the test sites. As the project was formed, most of the participants recognized the potential for the Vp/Vs ratio, determined from time measurements (t_s/t_p) on fully processed stacked record sections, as both an indicator of lithology and as a direct hydrocarbon indicator. Also, the difference in the response of P- and S-waves to gas saturation was recognized, and some of the approved test sites included lignite and, separately, gas-induced P-wave amplitude anomalies (bright spots). All data were recorded as two components, a P-wave component with a vertical vibrator and vertical geophones, and a separate pass over the line with a horizontal SH oriented vibrator recorded solely with horizontal (SH) geophones.

Overall, the group shoot was a success. Following the 24 months of acquisition, with each company providing its own independent interpretation, many of the original participants deployed shear-wave crews of their own. Further, a second phase of the group shoot, with a smaller number of companies, was initiated in Alberta, Canada.

Mechanical sources of direct shear-wave energy are shown in Figures 1 through 3. Figure 1 includes the SH-wave vibrator of the type used in the Conoco group project. Use of this type of vibrator requires an acquisition pass, separate from the P-wave acquisition, over the line. In this project, P-wave data were recorded with vertical geophones, and in the separate pass, SH-wave data collected solely with horizontal SH-wave geophones. Figure 1b is a close-up of the vibrator base-plate. The large pyramids on the base improve coupling of the horizontal plate motion to the earth. Figure 1c demonstrates the surface effects caused by the horizontal vibrator. A SH geophone, similar to those utilized in the Conoco group project, is illustrated in Figure 2. These geophones require both leveling and proper orientation to record high quality shear-wave data.

Figure 3 is an impulsive, directed source (Omnipulse) that simultaneously generates P- and SH-wave energy. The source impacts the base-plate at a controlled angle. By recording two different directions of motion, two separate records are available for processing. The two records contain P-wave data of like polarity and SH-wave data of opposite polarity. By taking sums and differences of the two records, P- and SH- wave data can be quite successfully separated. Further, only one pass of the source along the profile is required, provided both vertical and horizontal cross-line data are recorded simultaneously. Figure 4 is an ARIS source, a similar impulsive source to the Omnipulse, but capable of directing the impulse in any direction.

Figure 5 illustrates P- and SH-wave stacked data acquired with the horizontal vibrators and single P- and SH-wave geophones.

About the same time as the Conoco Vibroseis projects, some contractors, as well as major oil companies, were experimenting with two-component recording (vertical and in-line, or radial, horizontal components) of energy from a conventional, dominantly P-wave, source (dynamite or vertical Vibroseis). Some of these efforts continued well into the 1980's They did observe mode-converted shear-wave reflections in many cases (e.g., Garotta, 1987), but failed to successfully observe mode-converted shear-waves in some other areas. Several sources of this inconsistency could be described, but as we shall see below, one of the primary problems may have been the effects of azimuthal anisotropy, which cannot be corrected with the recording of only vertical and in-line data. With the recording of three components, however, it is possible to perform rotations of the observed data and often correct for at least the near surface effects of shear wave splitting associated with azimuthal anisotropy.

Simultaneous interpretation of P- and S-wave data requires unambiguous correlation of reflections between the two record sections. Figure 6 illustrates details of some of these correlations. Overall, the visual correlation of reflections between P- and S-wave data has proven to be less difficult than anticipated before the formation of the Conoco project.

The Conoco group shoot did include successful identification of gas (e.g., Ensley, 1984; Robertson and Prichett, 1985), estimation of gas thickness *in situ* (e.g., Tatham and Krug, 1985), observations of correlations of V_p/V_s in seismic intervals with the lithology of the same intervals (e.g., Tatham, 1985), discrimination between lignite induced and gas induced P-wave 'bright-spot' amplitude anomalies (e.g., Ensley, 1985; see Figure 7), variations in observed V_p/V_s with known variations in reservoir sand thickness, and other stratigraphic changes (e.g., Tatham and Krug, 1985). Significantly, the ability to visually correlate reflections between the P-wave and S-wave reflection section was established. Such a correlation is essential to estimating t_s/t_p (V_p/V_s) in a given stratigraphic interval.

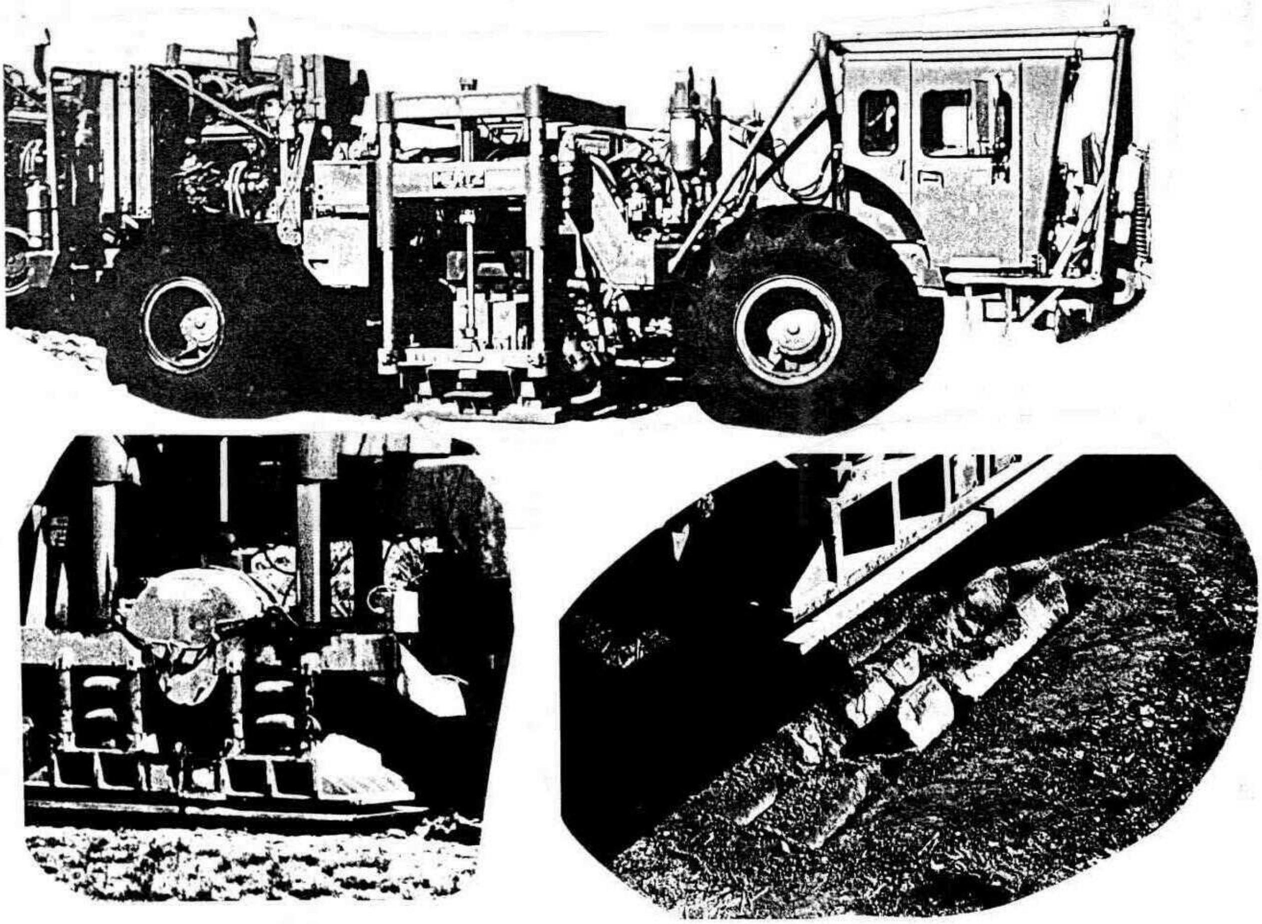


Figure 1. a.) Horizontal Vibroseis unit. b.) Detail of base plate. c.) Detail with base plate up, illustrating surface damage created by pyramids attached to base plate for coupling.

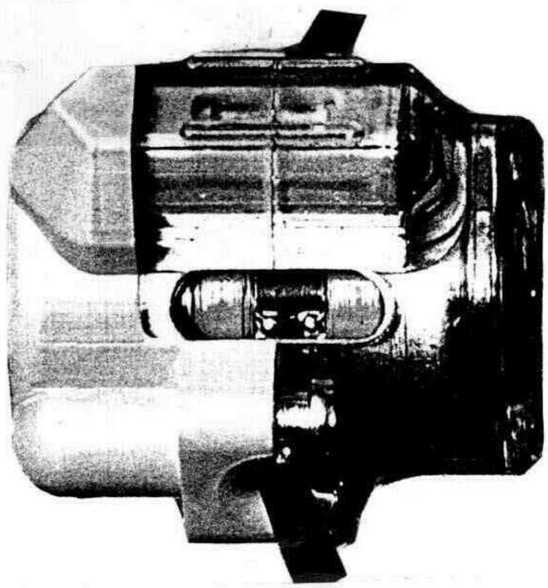
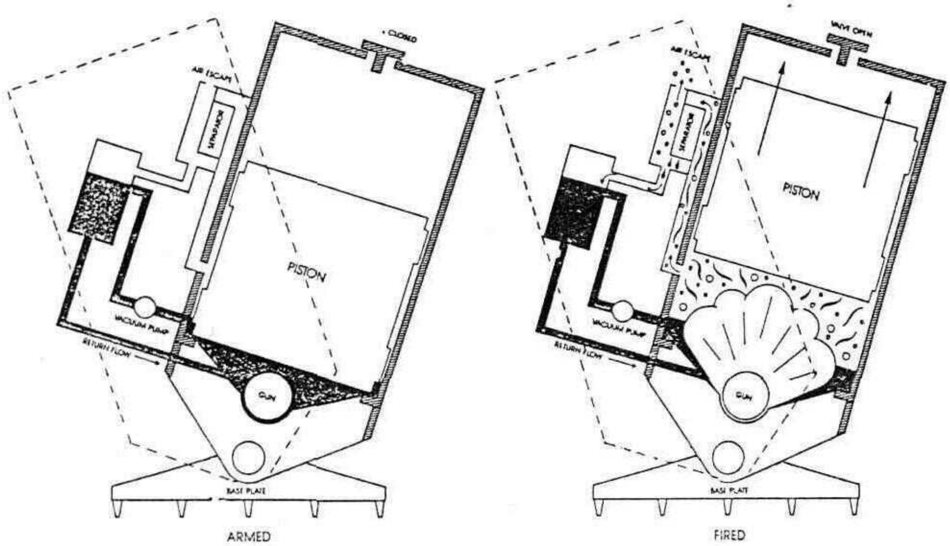


Figure 2. Single component horizontal geophone. For the surveys in question, these geophones were deployed in an cross-line (SH) configuration. Note leveling bubble.

(a)



(b)

Figure 3. a.) Omnipulse impulsive seismic source. Note tower with reaction mass that can be tilted to either side at an angle up to 45 degrees to produce SH-wave motion of opposite polarities. b.) Detail of Omnipulse operation with an air gun situated between the baseplate and a reaction mass (piston) in the tower. The release of compressed air in the air gun drives the baseplate into the ground while pushing the reaction mass up into the tower.

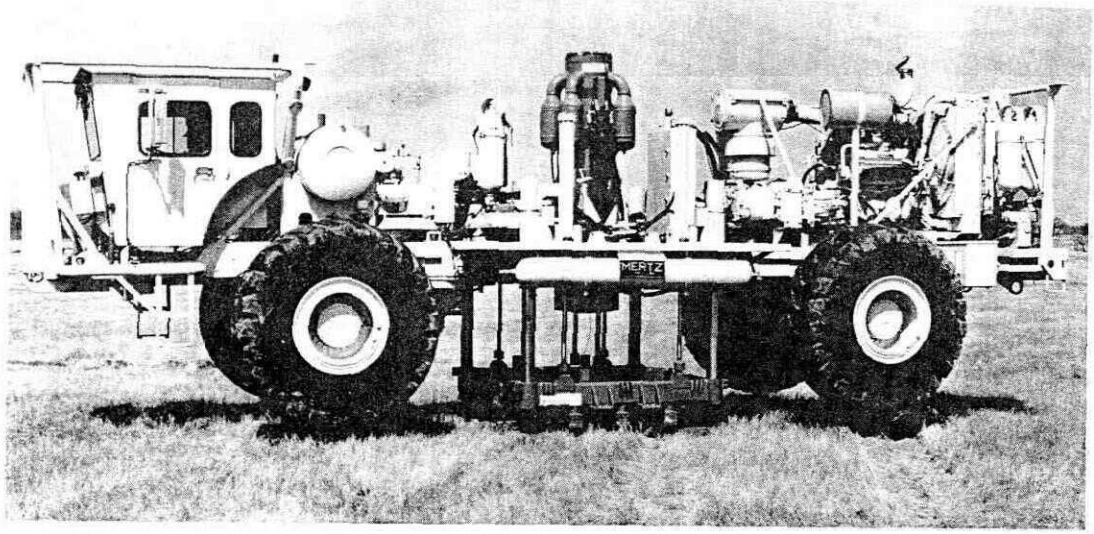


Figure 4. ARIS impactor seismic source. The polarized impulsive surface source is capable of generating directed impulses which can be resolved into three orthogonal source polarizations (P, SV, and SH) without changing the vehicle orientation.

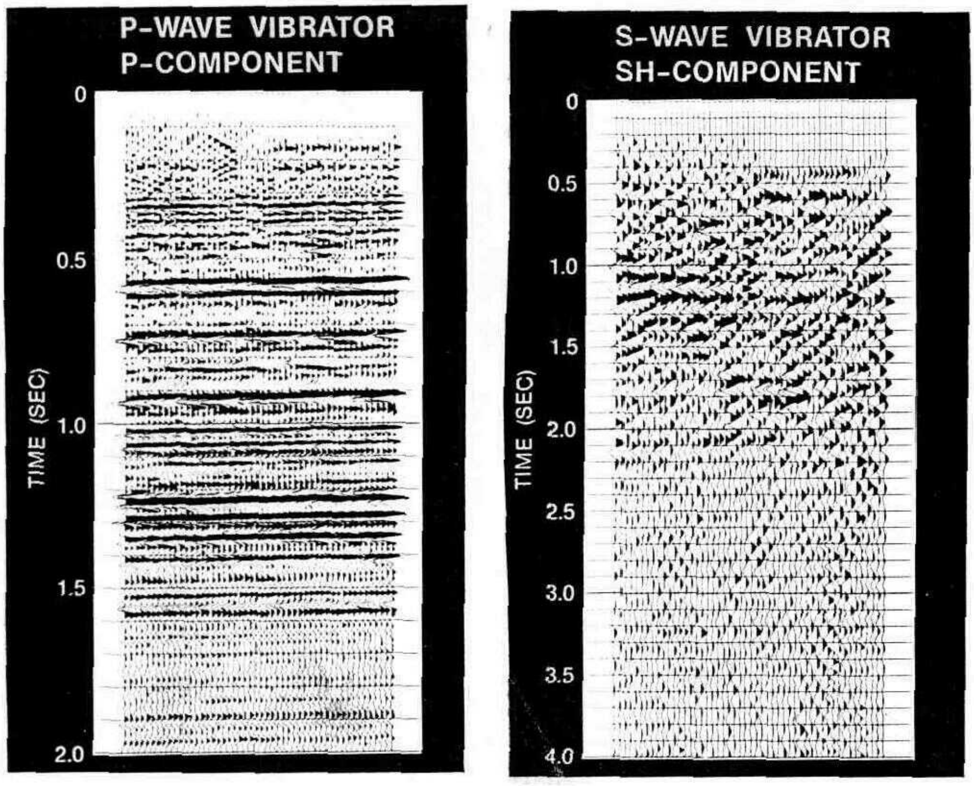


Figure 5. Examples of P and SH wave stacked data (Brute Stack) from the early Conoco Vibroseis project. Improved processing and vibrator controls have greatly improved the overall data quality in recent years.

Examples of successful demonstrations of the "interpretability" of P- and S-wave data are included in Figures 8 through 12. Figure 8 illustrates t_S/t_P ratios, equivalent to V_P/V_S, taken from a 10 mile long line of little or no lateral variation in lithology. The histograms show small scatter of the V_P/V_S values in different stratigraphic units, of differing lithology, and do demonstrate the response of V_P/V_S to variations in sand-shale percentages and to the dominance of limestone in one interval.

Figure 9 is a sample of P- and SH- wave data gathered with a Vibroseis source (P and SH, in separate passes over the line) over the Empire-Abo filed in southeastern New Mexico. Figure 10 is a map of the V_P/V_S ratio and the sand-shale percentages from well control. The depositional environment is a marine transgressive sequence in the lower Pennsylvanian Morrow formation.

Figure 11 shows the P- and SH-wave data gathered with an Omnipulse source (one acquisition effort, simultaneous recording of P and SH geophones) over the Scipio field in southern Michigan. There is little difference in the P- and SH- wave data, and minimal response on the individual sections, to the presence of the field.

The Vp/Vs values for several overlapping intervals are illustrated in Figure 12. The presence of the reservoir is associated with the dolomitization of the dense limestones of the Trenton-Black River unit. The differences in the V_P/V_S values for Limestone and Dolomite lead to an anomaly at the location of the field. Further, by considering overlapping stratigraphic units, the reliability of the interpretation is clearly improved.

With successful shear-wave interpretations becoming more common, a 'new' and potentially competing technology emerged--the recognition of the effects of observed variations in reflection amplitude with angle of incidence, or, alternately, offset (AVO). Ostander of Chevron published his first results in 1982 (Ostrander, 1982), and it became recognized that the slope of the near-linear relation between reflection amplitude and the square of the sine of the angle of incidence of a P-wave upon a reflector was dependent upon Poisson's ratio, which is wholly equivalent to the velocity ratio V_P/V_S. An alternative means of estimating the same parameters as extracted in shear-wave data, but from conventional, and generally existing, P-wave data appeared to be at hand. Thus, the interest in the more expensive shear-wave techniques waned temporarily. AVO did have some notable successes as a direct hydrocarbon indicator, and some limited success in estimating lithology. The consistent measurement of amplitude, however, is very difficult, especially on land data, and AVO, like most nascent techniques, displayed mixed results, especially for lithology estimation. In general, V_P/V_S estimated from the time observations on fully stacked P- and S-wave record sections are more stable than AVO observations requiring amplitude estimates on pre-stack data. The resolution of V_P/V_S, however, is limited to some identifiable unit of finite thickness, while AVO responds to changes across a single interface. Thus, direct V_P/V_S is a "lower-frequency" observation, while AVO interpreted variations represent a "higher-frequency" component. Moreover, long wavelength V_P/V_S variations determined from stacked P and S (or P-SV) sections are very stable, whereas the long wavelength component of V_P or V_S from either section alone is not. This should be of considerable importance for coupled P-P and S-S or P-SV inversion.

As more experience with shear-wave data was gained by the individual companies, the observations from the original group shoot could often be repeated but the resolution was often less than required for successful application to exploration

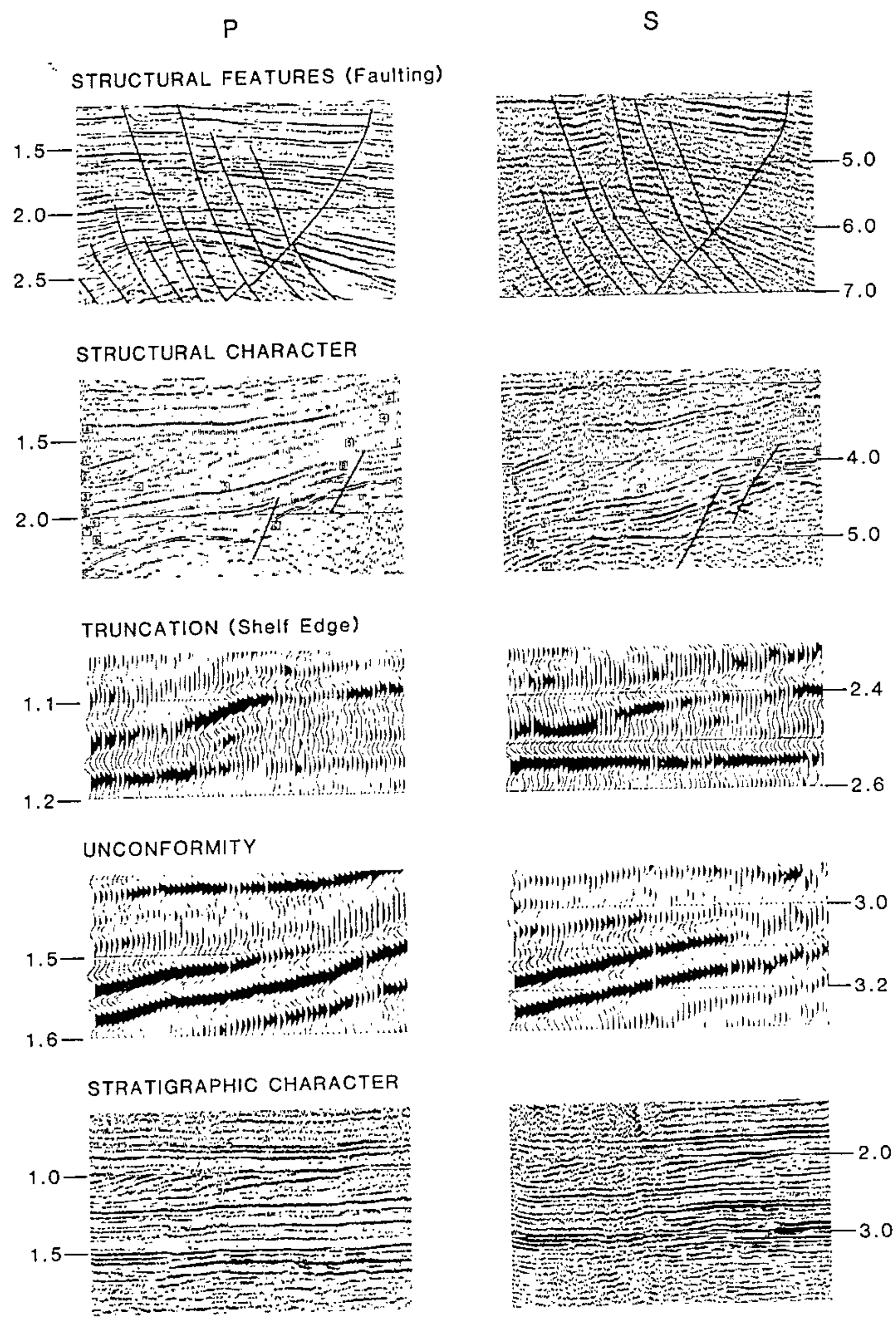


Figure 6. Stacked data examples of structural and stratigraphic similarities in P- and S-wave responses to the identical profiles. Several characteristics are useful in correlating P- and S-wave sections. (After Tatham and McCormack, 1991.)

problems. As vibrator hardware improved, those organizations that remained active in the techniques did reap some rewards. Further, one company (Fix *et al.*, 1987) found notable success in structural mapping with SH wave techniques in a region of severe ground roll, dominated by various modes of Rayleigh-wave motion, destroyed the P-wave data. Without the required near-surface low velocity channel to support Love-wave type surface wave interference, however, the SH wave reflections were successfully recorded.

One very significant development was the recognition, by Amoco scientists, of the effect of anisotropy on the overall quality of shear wave recording. In particular, azimuthal anisotropy was observed on all but two of the original Conoco test sites. One of the two exceptions involved unusable data in both the original Conoco data set and the Amoco data set, and one location simply showed no evidence of azimuthal anisotropy. Alford (1986) published some of these results at the EAEG meeting in June of 1986, which led to an entire series of publications at the subsequent fall SEG.

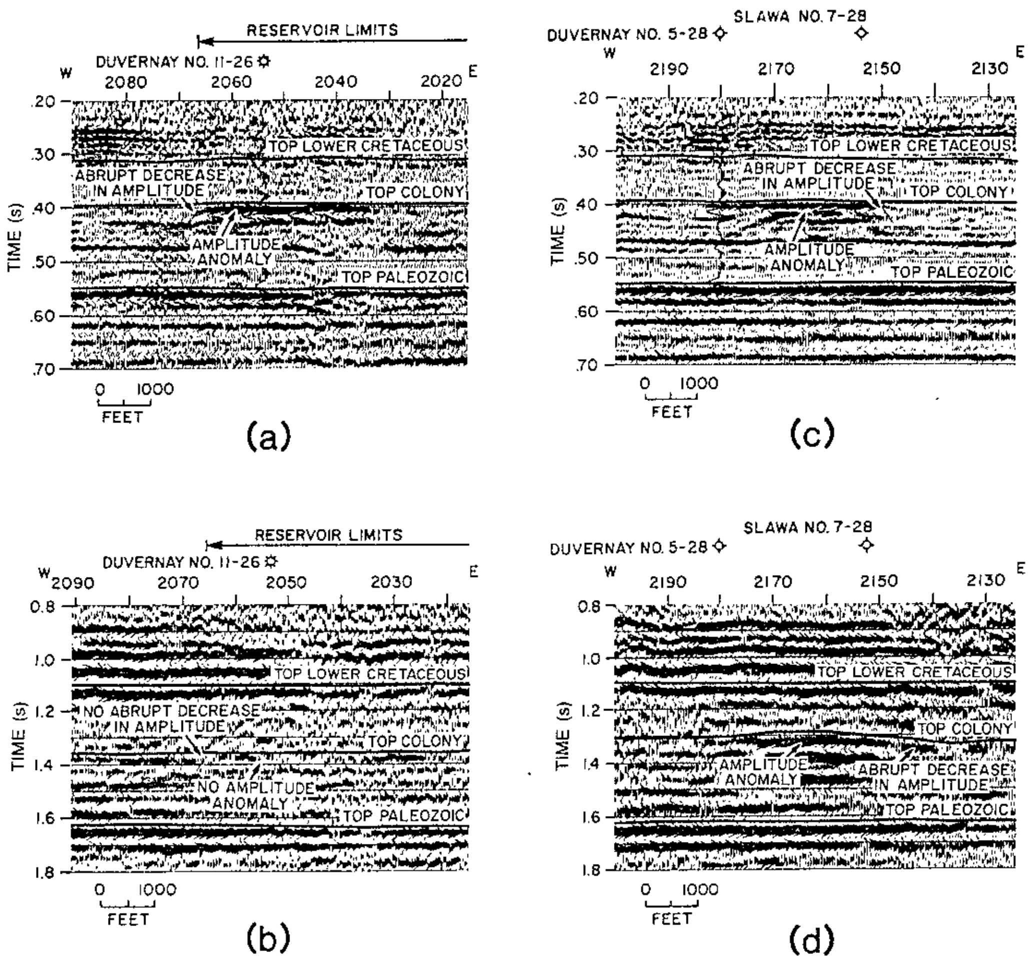


Figure 7. Comparison of reflections amplitudes of P-wave and S-wave data for a know gas field and a known coal seam at a similar stratigraphic position in the section. a.) P-wave response to a gas reservoir, illustrating characteristic amplitude anomaly. b.) S-wave response to the same gas reservoir. Note the conspicuous absence of an amplitude anomaly. c.) P-wave response, with amplitude anomaly, to a known coal deposit. d.) S-wave response, with amplitude anomaly, to the same coal deposit. (After Ensley, 1985.)

With this realization of the effects of azimuthal anisotropy, the potential for estimating fracture parameters in the subsurface was recognized, and a resurgence in interest in shear-wave recording occurred. Although, due to a strong downturn in the industry, only a slight resurgence in actual activity in shear wave seismic techniques was ultimately realized.

After Alford's publication other group-type studies emerged. Marshall Martin formed a small group to finance the acquisition of some multicomponent data, both source and receiver, for a line in the Silo Field of southeastern Wyoming. These data become the basis of his PhD dissertation at the Colorado School of Mines. He did observe correlations between his observed polarizations and the fracturing in the field (Martin and Davis, 1987). Further, some correlation between the degree of shear-wave splitting and the productivity was established. In addition, a small contractor organized a full nine-component survey (one line) over the Lost Hills field in Kern County, California. As a result of this success of the earlier Silo Field work and the interest expressed in the Lost Hills line, and full multicomponent (nine-component, or "9-C"-- three source polarizations each recorded by three component geophones) 3-D survey over the nearly two square miles of Silo field was organized. This was followed by similar, and in general larger, surveys over the South Casper Creek Field in Wyoming, the Cedar Hills Field (coal-bed methane production in the San Juan Basin) in New Mexico and the Joffre Field in southern Alberta.

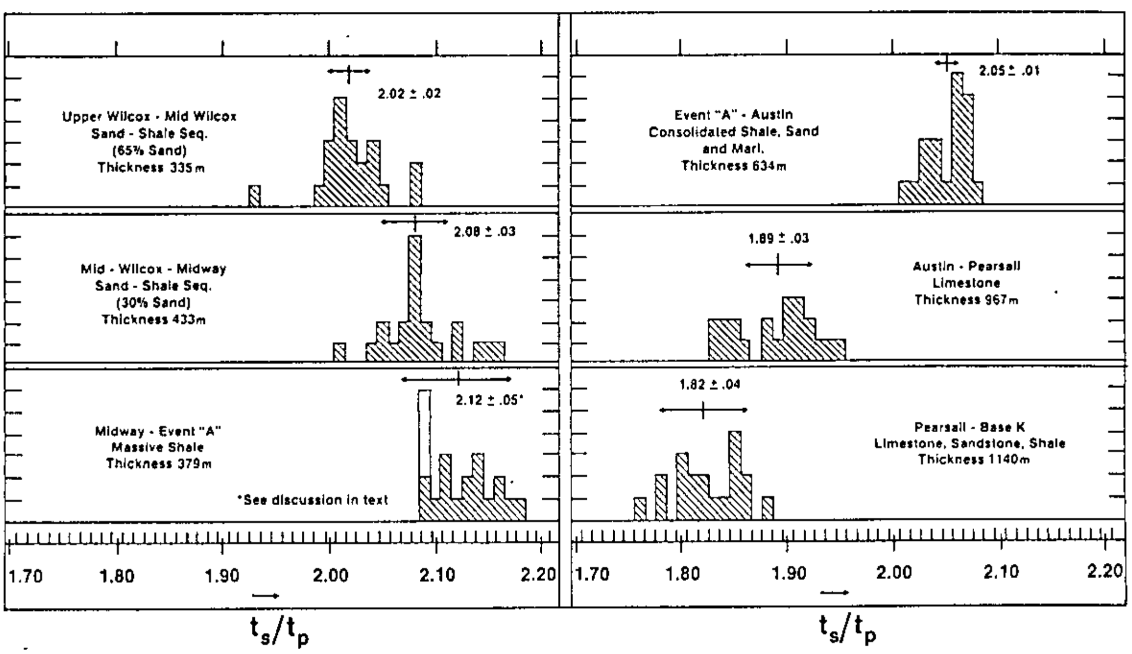


Figure 8. Histogram of individual t_s/t_p values for six intervals of chronostratigraphic rank series. The height of each block represents the number of values observed. Average t_s/t_p values and gross lithology in the interval are also indicated. Note the general increase in t_s/t_p values with increasing shale fractions in the first three intervals. The massive limestone in the Austin-Pearsall interval show t_s/t_p values of 1.89 +/- 0.03, within the 1.90 value often assumed for limestones. (After Tatham, 1985)

More recently, three-component recording of single-source data (dynamite or Vibroseis) has been studied in considerable detail (Eaton et al., 1991; Stewart, 1991; Harrison and Stewart, 1993). By simultaneously recording all three components, rotations to correct for shear-wave splitting are applied, where necessary. Further, AVO studies of P-SV, in addition to conventional P-P, are possible. Due to the asymmetry of the P-SV travel path and the migration of the P-SV conversion point toward the receiver location, significantly larger angels of incidence are realized for P-SV reflections than for P-P reflections at the same off-set. An important observation is that the stacked P-SV section has no physical meaning as a zero-offset reflectivity section. At zero offset there is no P-SV reflectivity for horizontal reflectors. The P-SV stacked section is actually an average of the reflectivity amplitudes over some range of offsets similar to the P-P section.

MARINE STUDIES

Suggestions of using doubly-converted PSSP data to gather shear-wave information in a marine setting--albeit with a 'hard' water bottom--were published by Tatham and Stoffa (1976). Following their suggestions of success, a physical model study demonstrating the recording of such shear-wave data was published (Tatham *et al.*, 1983). Following this success, a small survey was conducted off-shore Florida (Tatham and Goolsbee, 1984). This survey demonstrated the existence of shear-wave reflections that could be correlated with P-wave reflections down to a reflection time of two seconds. This demonstration led to a large group shoot that gathered approximately 600 km of large offset two-ship data offshore Florida (Tatham and Kasper, 1985).

The two-ship data displayed somewhat mixed results in terms of the quality of the shear-wave data. One suggestion for the differences was the possible effects of anisotropy. To test this possibility, it was suggested that several short lines, similar to the 1984 line, be shot over the same location as the 1984 survey. The lines were to have different azimuthal orientations, and thus test the data-quality vs. azimuth question. Further, direct recording of shear-wave on the sea floor at several locations along the lines was explored. With this in mind, two companies joined with the University of Texas Marine Science Institute to develop the required sea-floor recording capability and conduct the experiment. Unfortunately, due to changes in the industry environment, the experiment was never completed.

The earlier success of the physical modeling experiments suggested a repeat of the 1983 experiment, but with the inclusion of an anisotropic layer. A graduate student at the Allied Geophysical Laboratories at the University of Houston took on such a project, and completed a M.S. thesis in 1993. The results of this experiment were presented at the 1993 SEG meeting in Washington (Gregovic *et al.*, 1993). Overall, the effects of a shallow anisotropic layer were documented, and the variation in data quality of PSSP data with line orientation was established. Further, direct recording at the sea bottom (PSS) allowed for rotation of the recorded polarizations of the shear wave data, and a subsequent improvement in the data quality.

Applications of multiconverted reflections can readily be extended beyond the marine environment or to more complex contrasts in the marine environment. For example, Purnell *et al.* (1990) demonstrated the potential, through physical model studies, for using multiconverted wave for subsalt imaging in the Gulf Coast area offshore Louisiana. The shear-wave velocity in salt fairly closely matches the P-wave

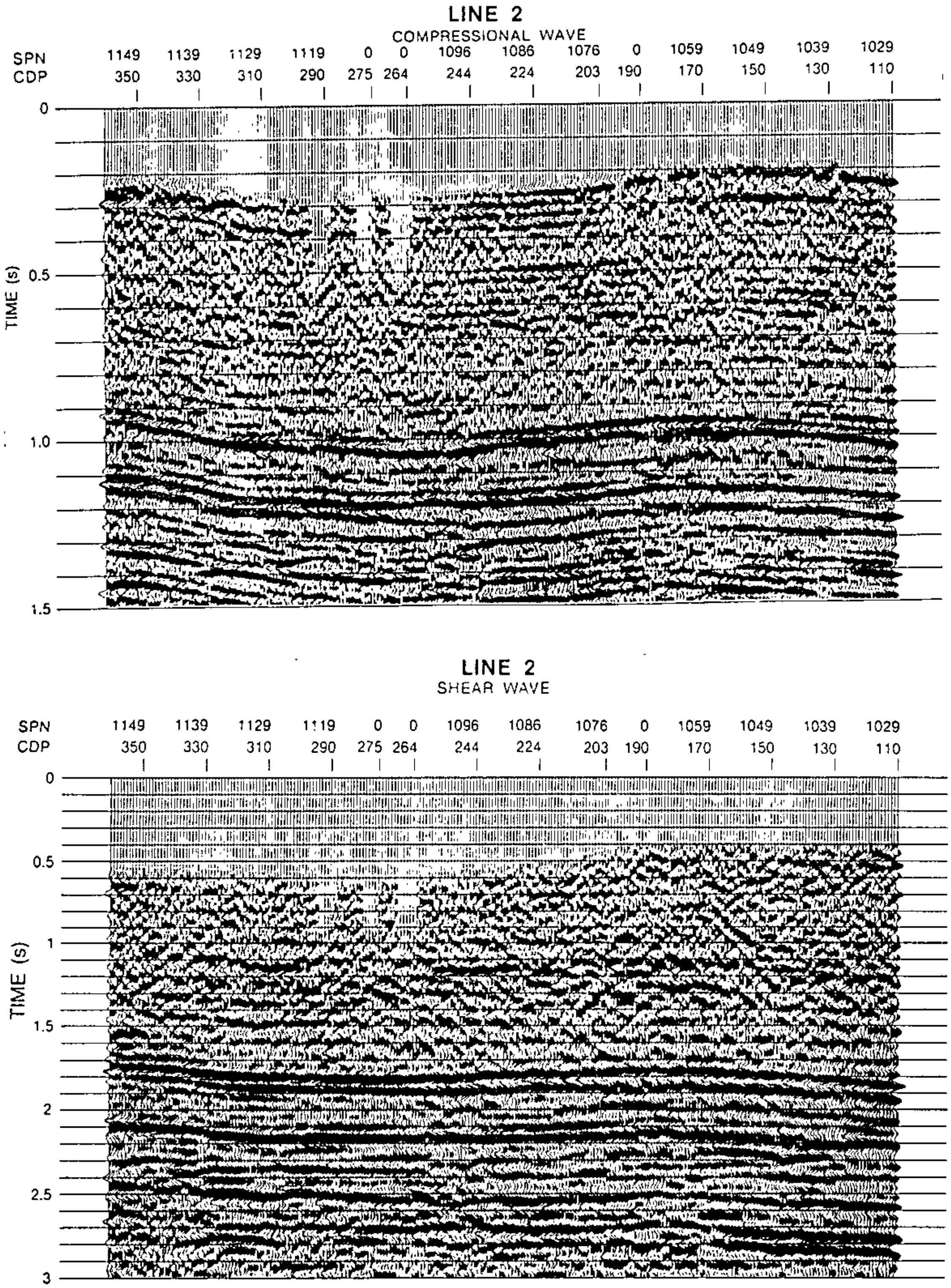


Figure 9. Stacked CMP P- and SH-wave sections for line 2 of the Empire-Abo field. The Morrow sand is near a reflection time of 1.25 s on the P-wave data and 2.5 s on the S-wave data. (Aftr McCormack *et al.* 1985.)

velocity in the surrounding sediments, so by exploiting the converted shear-wave energy in the salt, the ray-tracing becomes simpler than entire raypaths of P-waves, and imaging beneath the salt may be more robust and stable by applying multiconverted waves.

In a more complex stetting, Chen and Lawton (1992) suggested PSSP for penetrating the frozen permafrost at the sea floor in the Canadian Beaufort Sea. They further complicate the situation by considering an ice layer floating on the sea surface, frozen permafrost at the sea floor, and lower velocity sediments beneath the permafrost. Thus they can have reflections of PSSP and PSPPSP, as well as other types, present.

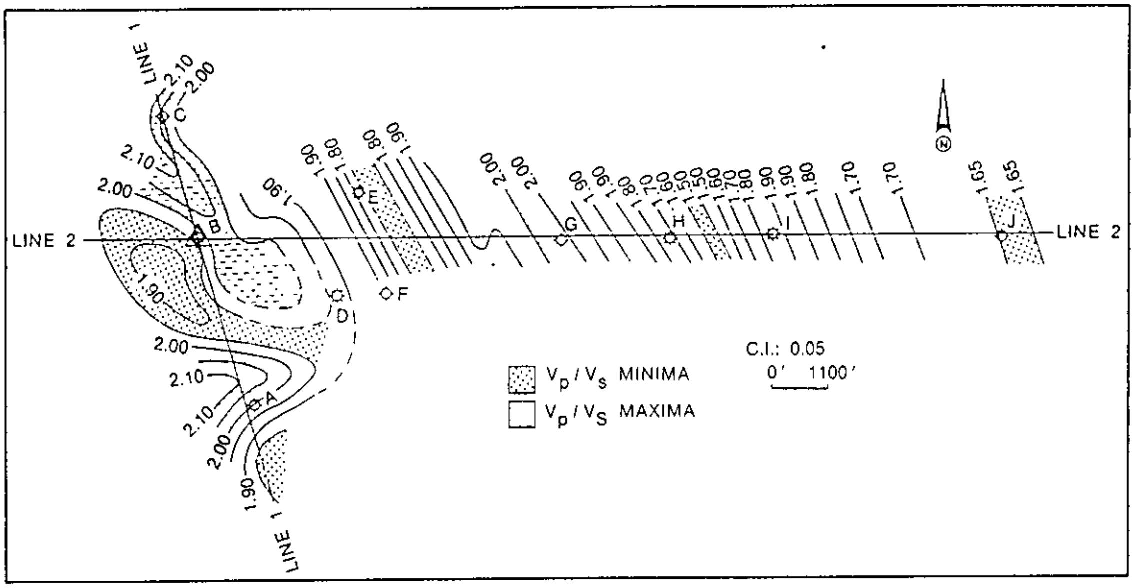


Figure 10. Contour map of seismically derived V_p/V_s values along lines 1 and 2. Minima in V_p/V_s correspond to greater sand percentages, shale maxima in V_p/V_s correspond to greater shale (lesser sand) percentages. (After McCormack et al., 1985)

BOREHOLE DATA

VERTICAL SEISMIC PROFILES (VSP)

One area of relatively high activity is in nine-component VSP's. The data sets are relatively limited in magnitude, and an acquisition project can often be completed in 24-48 hours. The anisotropy information provided is often interpreted to yield estimates of fracture orientation, variations in orientation with depth, and some sense of variations in fracture intensity (e.g., Winterstein and Meadows, 1991a,b). Working in a well bore requires no trespass permits for the large vibrators, and they generally operate from fixed positions. Further, no elaborate field procedures, beyond mobilizing the sources, is required.

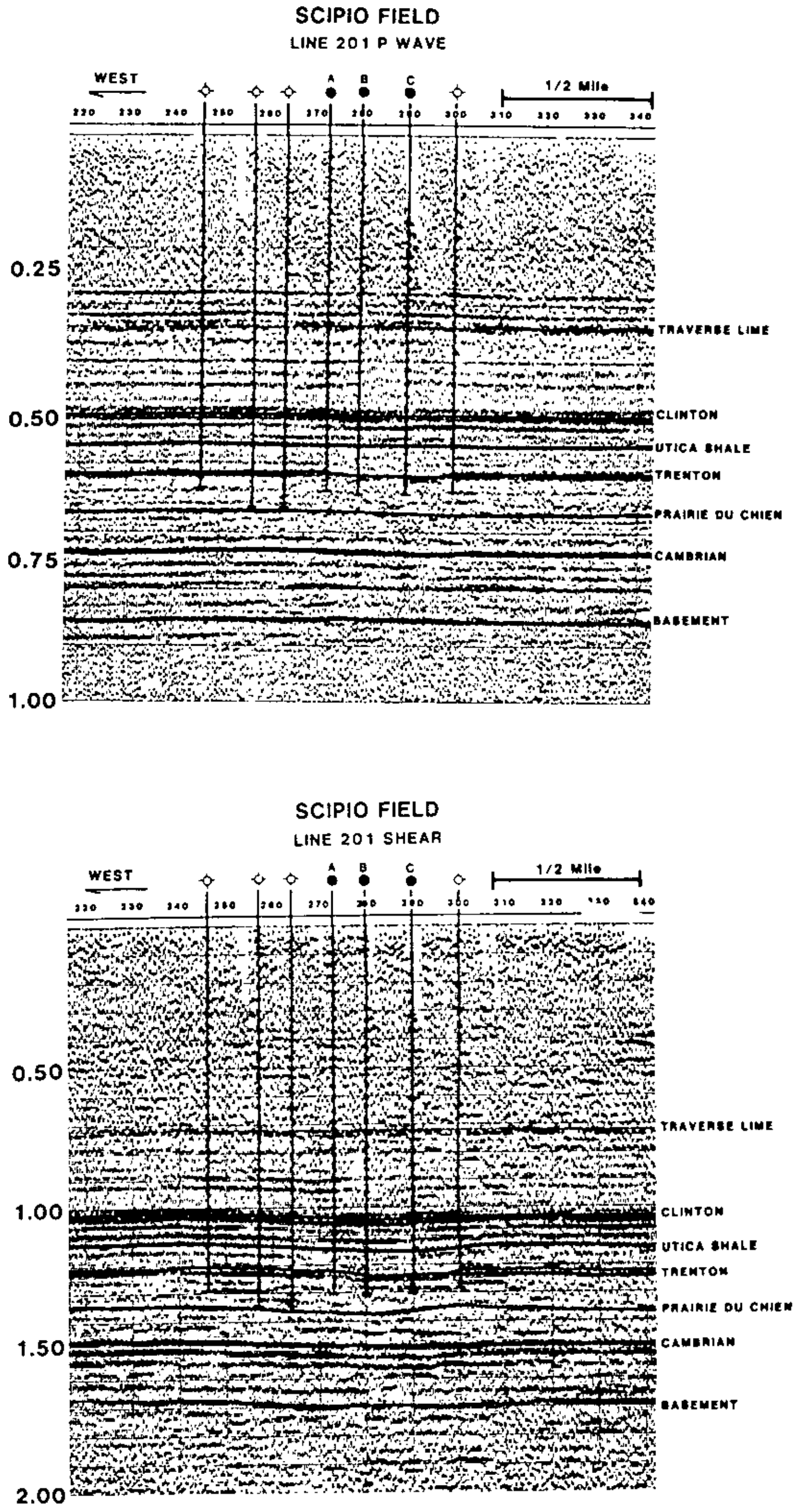


Figure 11. A portion of a.) P-wave data and b.) S-wave data for a line traversing the Scipio filed in southern Michigan. Note the overall lack of structural character associated with the production. The interpretation shown in Figure 12 is based upon computing t_S/t_P values for various intervals, including overlapping intervals, between the statigraphic markers identified on the sections. (After Pardus *et al.*, 1990.)

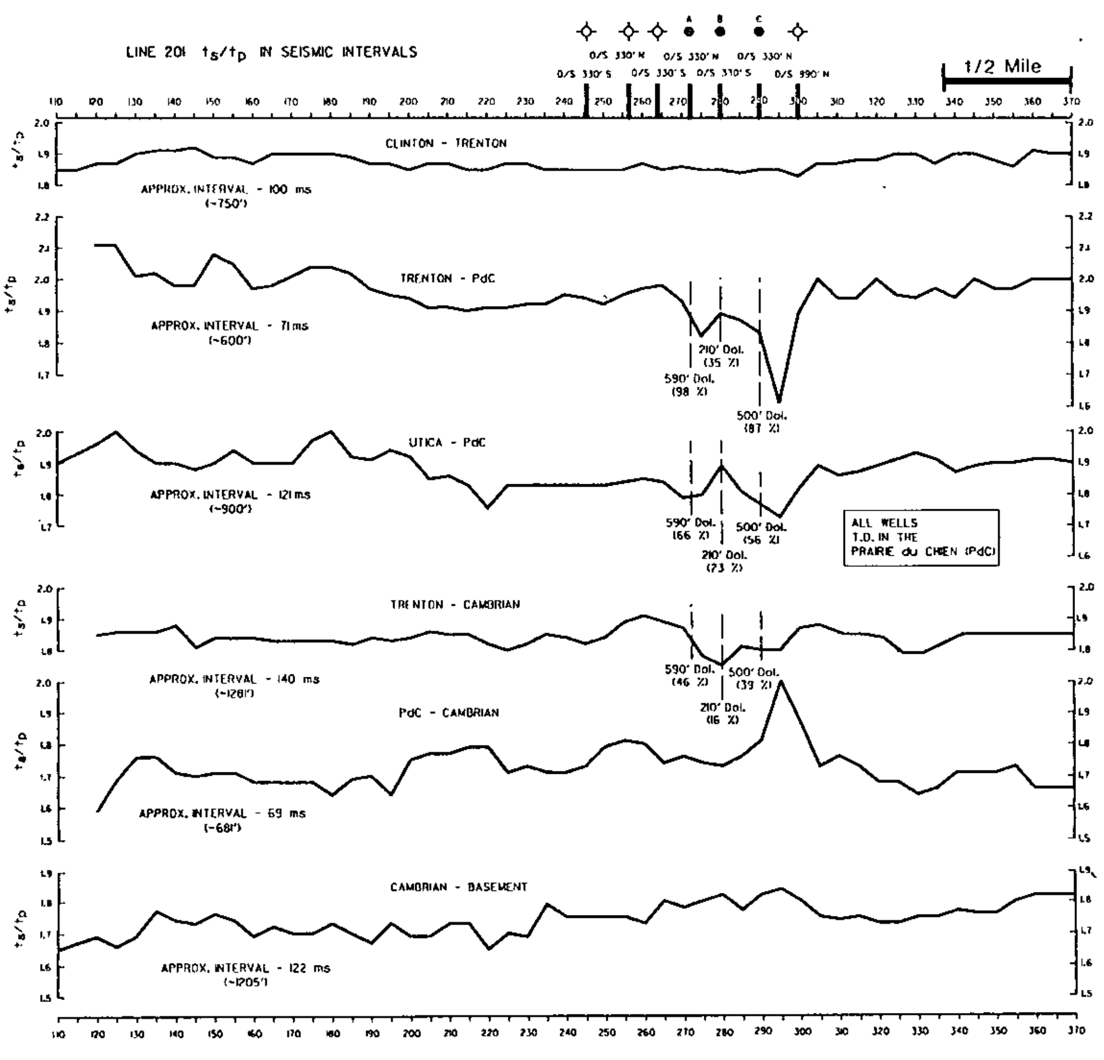


Figure 12. Profiles of t_S/t_P values for five stratigraphic intervals computed from the stacked P- and S-wave data over the Scipio field shown in Figure 11. Three different intervals contain the prospective Trenton formation, and all show anomalies associated with the presence of dolomite in the Trenton carbonate unit. Other units provide redundancy in the observations that improve the reliability of t_S/t_P interpretation over the seismic traverse. (After Pardus *et al.*, 1990).

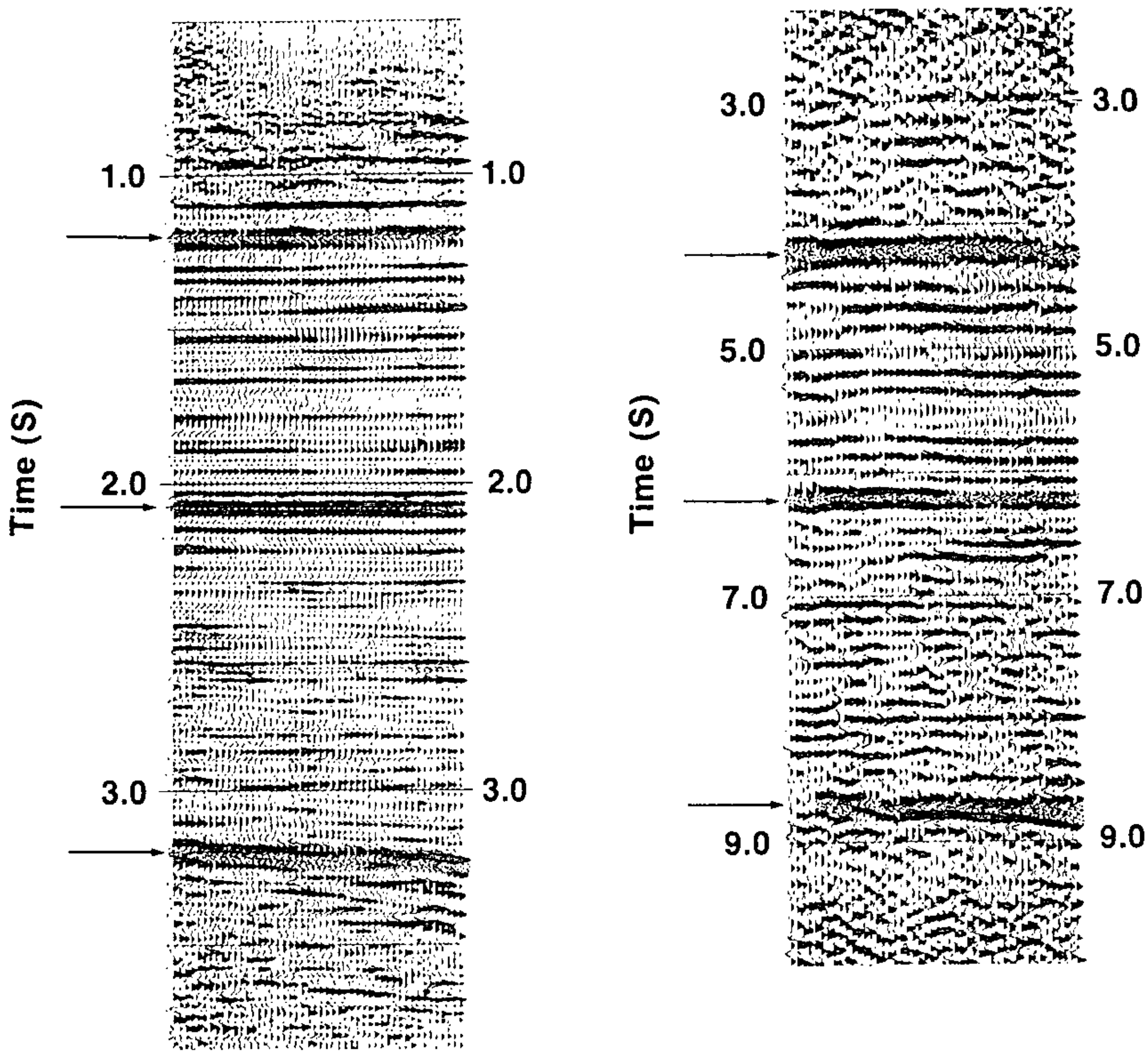


Figure 13. P- and SH-wave expanded reflection sections gather in southern Louisiana. The arrow marks show the correlation in the reflection events between the P- and S-wave data, as well as the VSP data in Figure 14. (After Corbin *et al.*, 1987)

Often, fracture information may be acquired from borehole imaging logs. The VSP data, however, generally samples a volume to include a zone meters to several tens of meters away from the borehole. Thus, the observations may not depend upon fractures intersecting the borehole. There is usually an implicit assumption in VSP interpretation, however, that there is only one fracture orientation, and that the fractures are nearly vertical. Similar argument can be made for recorded direct shear-wave energy in dipole shear-wave logs

Figure 13 is an example of P- and SH-wave reflection profiles gathered over a well with P- and S-wave VSP surveys. Figure 14 represents data from the P- and S-wave VSPs. Correlated reflections are indicated in both of the figures. The principal reflections are comfortably correlated. Note the overall similarity in the structural character of the reflections. Figure 15 illustrates P and mode-converted SV- wave data from a near-offset VSP. Again, note the correlation of the prominent seismic markers. These data are well suited to V_p/V_s interpretations

DIPOLE LOGGING

Logging with direct shear-wave tools is now a reality (Zemanek *et al.*, 1991). These direct shear-wave logs have been run in both 'fast' and 'slow' formations, providing the opportunity to correlate both P- and S-wave seismic data directly to the log suite. Further, by considering two polarizations of the shear-wave, information on shear-wave splitting, and fracture orientation, is available. The interpretation of crossed-dipole shear-wave logs is very similar to the nine-component VSP. In the case of the logging, however, the wavelengths are on the order of meters rather than tens of meters, and the depth of penetration away from the borehole is typically meters. Like the VSP data, there is no necessity for the fractures to intersect the borehole.

CROSS-WELL

Another borehole use of shear waves is in the crosswell geometry. Numerous investigators have commented on the richness of wave types emitted by a down hole source (e.g., Pratt and Goultz, 1991). Shear waves are especially evident. Khalil et al. (1993) developed a processing flow for transmitted and reflected shear waves in a crosswell production environment. As illustrated in Figure 16. they were able to form interpretable images from these data.

WHERE ARE WE NOW?

Most applications of direct shear wave sources and multicomponent recording now focus on controlled polarization with the goal of estimating fracture parameters. This requires large mechanical sources to generate P, SH and SV energy directly. Each source orientation is then recorded by three-component geophones, which leads to full 9-component recording. Overall, field operations with these sources is quite expensive. A simpler, and less expensive, field technique would be welcome.

There is considerable activity in conventional source (single component) 3-component receiver recording. This method is logistically simpler and less expensive than "9-C" recording. Both P-P and P-SV sections are created from these data. Applications of P-SV sections include t_s/t_p analysis for lithology, thin bed imaging, imaging interfaces with differing S- and P-wave properties, avoiding short-path P-P

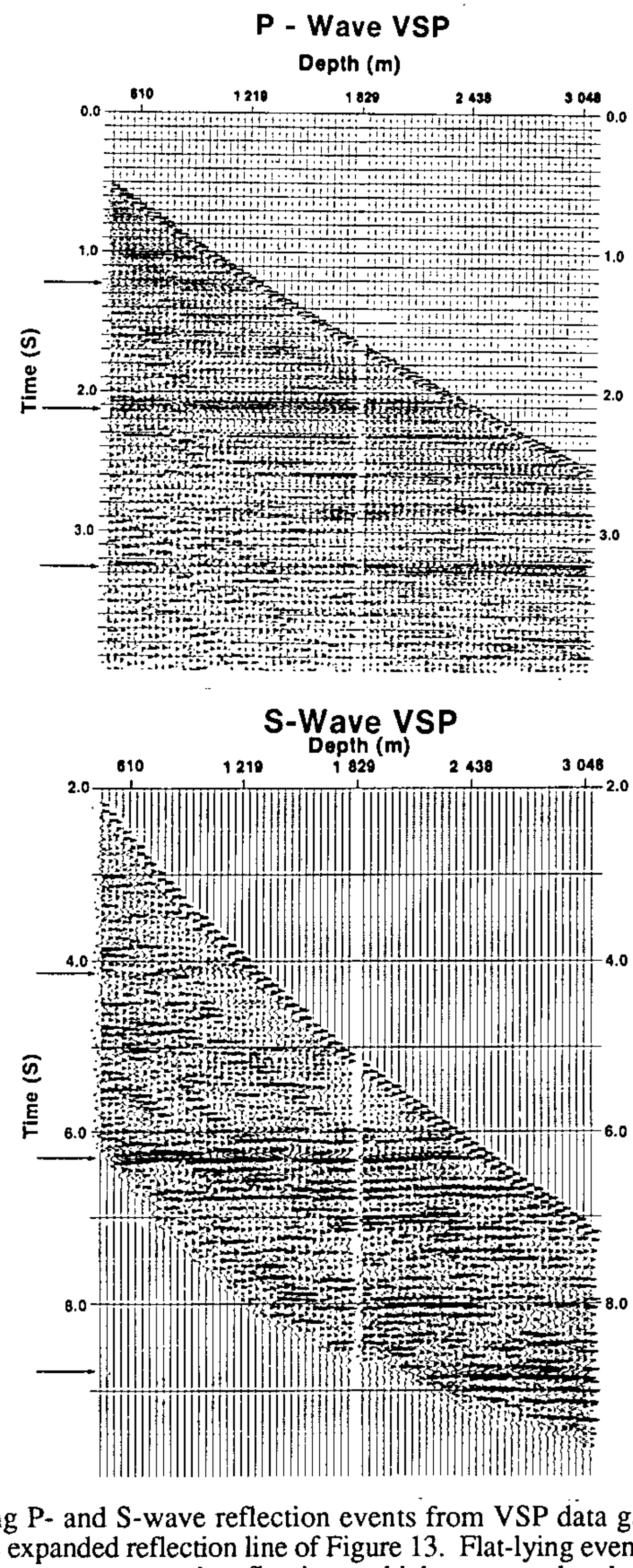


Figure 14. Upgoing P- and S-wave reflection events from VSP data gathered at the lame location as the expanded reflection line of Figure 13. Flat-lying events are primary reflections. The three arrows mark reflections which are correlated to the surface reflections of Figure 13. (After Corbin *et al.*, 1987.)

multiple contamination, and estimating S-wave propagation. Overall, any t_S/t_P that can be done with direct shear-wave data can be done with P-SV data, if data quality is sufficient. Thus, with improvements in acquisition and processing techniques, affordable shear-wave data for lithology and direct hydrocarbon indication may be nearly at hand.

WHERE ARE WE GOING?

A large part of the future lies in three-component seismic recording of single-source data to enhance converted P-wave sections and generate additional S-wave information. Although the only control on the source polarization (at least in an isotropic medium) is the source-receiver azimuth, three-dimensional surveys with a variety of source-receiver azimuths may provide part of the answer. Further, Alford-like rotation--developed at CREWES for only one source component and two receiver components--of all data prior to interpretation should improve the over-all quality. In general, SV data is more difficult to process than SH data. This results from the presence of anisotropy due to layering in the subsurface, particularly the fine-bedding in shale units, and the consequent complications in stacking velocities. As greater understanding of these processes is realized, however, problems can be addressed and corrected.

Further improvements in P-SV data acquisition and analysis will be useful, especially in the 3-D geometry.

One intriguing direction is simultaneous use of V_P/V_S data from P-SV and P-P sections and AVO variations computed from both P-P and P-SV reflections. By using both P-P and P-SV AVO curves, greater redundancy and reliability of the AVO interpretations is realized. Further, as mentioned earlier, the AVO data represent "high-frequency' variations. The V_P/V_S, being more stable, but 'lower-frequency' than the AVO variations, can act as a low-frequency component to set limits and constrain averages over the section for the AVO interpretations. This would be similar to low-frequency velocity control in the inversion of reflection coefficients to a synthetic acoustic log. In this case, however, the low frequency components are quite well defined from the two seismic data sets. In general, V_P/V_S estimated from the time observations on fully stacked P- and S-wave record sections are more stable than AVO observations, which require amplitude estimates on pre-stack data. The resolution of V_P/V_S however, is limited to some identifiable unit of finite thickness, while AVO responds to changes across a single interface. Thus, direct V_P/V_S is a "lower-frequency" observation, while AVO interpreted variations represent a "higher-frequency" component. As discussed earlier, long wavelength V_P/V_S variations determined from stacked P and S (or P-SV) sections are very stable, whereas the long wavelength component of V_P or V_S from either section alone is not. This possible combination of input could lead to more stable coupled P-P and S-S (or P-SV) inversion.

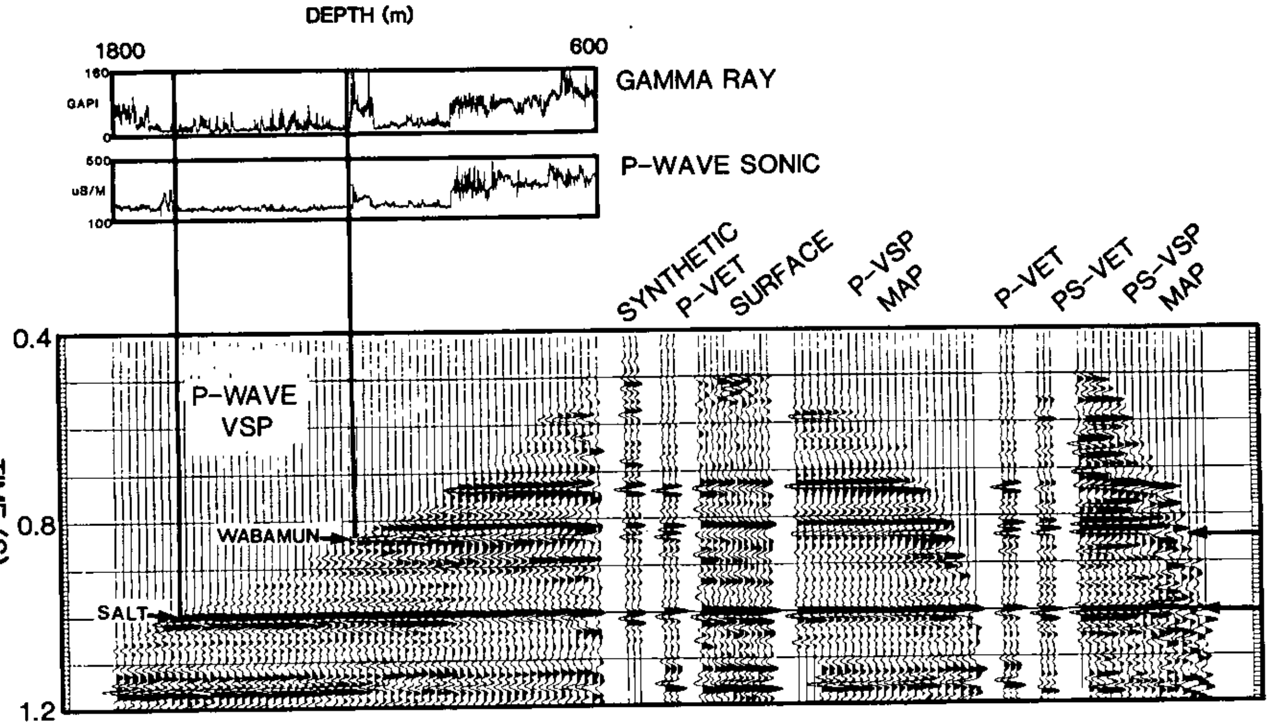


Figure 15. Display incorporating various P-wave and P-SV wave data. In particular, P-wave VSP refection data is at left hand side of the display, and P-SV reflection data at the far right hand side of the display. Event are correlated, and all time traces are displayed trace normalized. (After Geis *et al.*, 1990.)

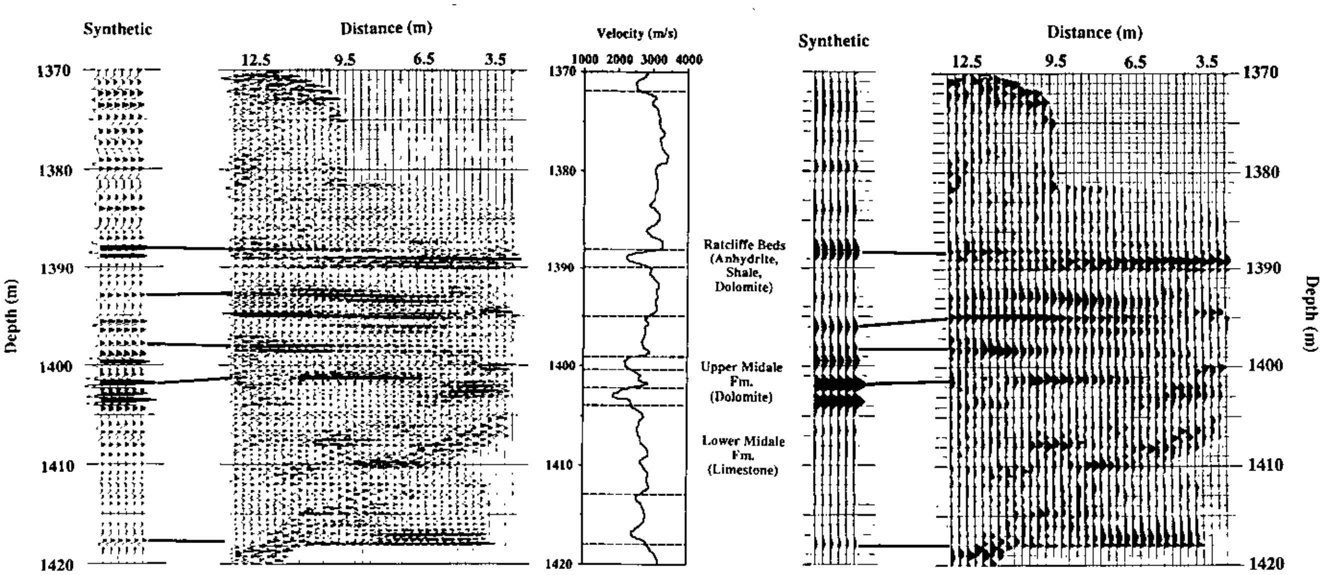


Figure 16. Display of final interpretations of cross-well reflection S-wave data. Downhole sources commonly generated considerable S-wave energy. a.) S-wave synthetic seismogram generated from S-wave sonic log shown in c.). b.) Final cross-well section from stack of nine receiver maps. c.) S-wave sonic log. d.) Instantaneous amplitude of synthetic seismogram in a.) e. The instantaneous amplitude of the final section in b.) (After Khalil *et al.*, 1993.)

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