FINAL REPORT

EXPANDING CONVENTIONAL SEISMIC STRATIGRPHY INTO THE MULTICOMPONENT SEISMIC DOMAIN

by

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ABSTRACT

Multicomponent seismic data are composed of three independent vector-based seismic wave modes. These wave modes are, compressional mode (P), and shear modes SV and SH. The three modes are generated using three orthogonal source-displacement vectors and then recorded using three orthogonal vector sensors. The components travel through the earth at differing velocities and directions. The velocities of SH and SV as they travel through the subsurface differ by only a few percent, but the velocities of SV and SH (Vs) are appreciably lower than the P-wave velocity (Vp). The velocity ratio Vp/Vs varies by an order of magnitude in the earth from a value of 15 to 1.5 depending on the degree of sedimentary lithification.

The data used in this study were acquired by nine-component (9C) vertical seismic profile (VSP), using three orthogonal vector sources. The 9C vertical seismic profile is capable of generating P-wave mode and the fundamental S-wave mode (SH-SH and SV-SV) directly at the source station and permits the basic components of elastic wavefield (P, SH-SH and SV-SV) to be separated from one another for the purposes of imaging. Analysis and interpretations of data from the study area show that incident full-elastic seismic wavefield is capable of reflecting four different wave modes, P, SH , SV and C which can be utilized to fully understand the architecture and heterogeneities of geologic sequences. The conventional seismic stratigraphy utilizes only reflected P-wave modes. The notation SH mode is the same as SH-SH; SV mode means SV-SV and C mode which is a converted shear wave is a special SV mode and is the same as P-SV.

These four wave modes image unique geologic stratigraphy and facies and at the same time reflect independent stratal surfaces because of the unique orientation of their particle-displacement vectors. As a result of the distinct orientation of individual mode's particle-displacement vector, one mode may react to a critical subsurface sequence more than the other. It was also observed that P-wave and S-wave do not always reflect from the same stratal boundaries. The utilization of full-elastic seismic wavefield needs to be maximized in oil and gas explorations in order to optimize the search for hydrocarbons.

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INTRODUCTION

The utilization of seismic stratigraphy has been a dominant force in the field of seismic interpretation since the fundamentals of seismic stratigraphy were introduced by Exxon geoscientists in the mid-1970's (Payton, 1977). We are aware of the fact that seismic stratigraphic analyses revolve on recognition of seismic sequences and facies across a seismic grid and utilization of spatial geometries, arrangements, and distributions of these sequences and facies to determine depositional environments, lithfacies and internal architecture of the earth's subsurface.

Multicomponent seismic stratigraphical studies called elastic-wavefield seismic stratigraphy has been found to expand seismic stratigraphy into a new dominant science in oil and gas exploration. The basics of elastic-wavefield seismic stratigraphy is that any component of the multicomponent seismic wave-field can provide unique seismic facies information across some stratigraphic intervals that cannot be observed by other components of the wave-field. The science of the elastic-wavefield seismic stratigraphy is that a multicomponent seismic wave-field tests the properties of the earth in three orthogonal directions (fig.1), making the displacement vector of one mode to detect internal structure of the earth differently from other modes. It was observed that each mode has a unique reflectivity equation that relates its reflection capability and phase to the elastic impedances of the earth. These differing reflectivity equations are commonly the most compelling evidence for convincing scientists that elastic-wavefield seismic stratigraphy is built on a sound base.

The result is that the internal complexities and heterogeneities within the earth can be characterized with seismic stratigraphy. Traditionally, most oil reservoir characterization are done with only compressional P-wave seismic data. The full science of reservoir characterization can be achieved by incorporating the principles and applications of vector-wave field seismic data in which geologic systems are interpreted using both P-wave and shear (S) wave images of subsurface stratigraphy. This is so, because, sometimes spatially coincident P and S seismic profiles do not show the same reflection sequences or the same lateral variations in seismic facies character.

EXECUTIVE SUMMARY

The application of the knowledge of vector is paramount for multicomponent seismic technology development. Traditionally, seismic stratigraphy was based on scalar which made it unnecessary to know the direction in which each component of the multicomponent elastic-wavefield moved in the earth. In multicomponent seismic stratigraphy, it is necessary to know the direction of the earth displacement before any action is taken to generate, process or interpret multicomponent seismic data. To effectively carry out multicomponent survey that will produce all possible wave modes, each source satation must have sources that create three orthogonal source-displacement vectors (fig.11). A good example of three vector-based vibrator sources positioned at a source station to create such orthogonal (fig. 2). If the sources do not create the vectors, some wave modes will not be propagated. At the same time, if three orthogonal vector sensors are not at all receiver stations, some wave modes created by these orthogonal source-displacement vectors will not be recorded.

Multicomponent seismic data are composed of three independent vector-based seismic wave modes. These wave modes are, compressional mode (P), and shear modes SV and SH. The three modes are generated using three orthogonal source-displacement vectors and then recorded using three orthogonal vector sensors. The components travel through the earth at differing velocities and directions. The velocities of SH and SV as they travel through the subsurface differ by only a few percent, but the velocities of SV and SH (Vs) are appreciably lower than the P-wave velocity (Vp). The velocity ratio Vp/Vs varies by an order of magnitude in the earth from a value of 15 to 1.5 depending on the degree of sedimentary lithification.

The physical characteristics and properties of the internal structure of the earth are contingent upon the direction in which the structure is tested. Different elastic constants are sensed when the earth is displaced perpendicular to its bedding planes versus being displaced parallel to the planes, or when the earth is displaced perpendicular to fractures versus parallel to fractures. The particle-displacement vector of a P-wave component senses the earth's internal structure in only one direction-the direction in which the P component is propagating, (fig 1).

The study of multicomponent seismic stratigraphy is exciting in that P, SH, SV wave components sense the earth's internal structure in three orthogonal directions, (fig. 12). Each wave mode carries unique earth-internal structure data, such as reactions to elastic constants, cementation quality, porosity, rock type, fluid type, and orientation of anisotropy axes as it leaves to receiver stations.

To fully understand multicomponent seismic stratigraphy, three orthogonal source-displacement vectors are created at source stations, (fig, 2,11) and three orthogonal vector sensors record these distinct wavefields. When these configurations are in pace and carried out, the result is nine-component (9-C) seismic data. The nine-component data comprises of the wave modes, P-P, SH-SH, SV-SV, P-SV, and SV-P, in which the term preceding the hyphen means downgoing wave mode and the term following the hyphen means upgoing wave mode.

Three-component (3-C) seismic data are created when three orthogonal vector sensors occupy the receiver stations, but only a P-wave (single displacement) or 1-C) source is used to create the illuminating wavefield.. Only two wave modes are generated by 3-C data, P-P and P-SV modes.

If a shear wave propagates in the internal of the earth that has vertical fractures or consistent tectonic orientation of the maxmum horizontal stress, vector will segregate into daughter modes, fast-S and slow-S. these daughter modes travel at different velocities, as their names imply, and they have orthogonal, not parallel displacement vectors. The displacement vector of the fast-S mode is oriented parallel to the symmetry plane that is parallel to the vertical fractures. The displacement vector of slow-S mode is oriented normal to this symmetry plane. Figure 13 shows different ways of acquiring multicomponent seismic data and specific wave components associated with each acquisition procedure.

The basic principle of seismic stratigraphy is that a seismic reflection event images a surafce of geologic sequence. The imaging of geologic sequence is accomplished by introducing an incident full-elastic seismic wavefield into the subsurface geologic sequences.
The incident full-elastic seismic wavefield reflected four different wave modes, P, fast-S (SH), slow-S (SV) and C. These four wave modes reflect independent stratal surfaces and image different geologic architecture and facies. These wave modes were generated by nine-component vertical seismic profile.

The 3-D, 9-component data were recorded using midpoint imaging concepts that are standard practice in the oil and gas industry. Three orthogonal vibrators used to generate 9C (9-component) VSP (vertical seismic profile) are vertical vibrator, inline horizontal vibrator and crossline horizontal vibrator. The geometry of the three orthogonal vibrators created stacking bins measuring 110 ft x 82.5 ft across the image space, with a stacking fold of 20 to 24 in the full-fold area of each data acquisition grid. The recording template that moved across the image space consisted of six parallel receiver lines, each spanning 96 receiver stations. Three-component geophones were deployed at each receiver station of this 3-D grid. Each receiver string deployed at a receiver station contained three 3-C geophones, and all three geophones were positioned in an area spanning 3 to 5 feet to form a point array. The geophones were planted carefully to position one horizontal element in the inline direction (the direction that the receiver line was oriented) and the second horizontal element in the crossline direction.

Large (52,000 lb) vibrators were used to generate the 9-component data. Three distinct sets of vibrator units occupied each of the source stations. Vertical vibrators comprised one of these source arrays. These vertical vibrators generated a wavefield that was dominated by P-waves, and that wavefield was recorded by the rectangular grid of 3-component sensors in the recording template that was centered on the source station. S-wave dominated wavefields were generated by horizontal vibrators. One set of horizontal vibrators applied a shearing motion in the inline direction at each source station, and a second set of horizontal vibrators applied a shearing motion in the crossline direction. The wavefields produced by these two distinct polarized S-wave sources were recorded as individual records by the 6-line template of 3-C receivers centered on the active source station.

Data analysis shows that P-wave and S-wave do not always reflect from the same stratal boundaries. At inline coordinate 2100 and crossline coordinates of 10,380, 10430, 10480 and 10,520 the P-wave stratigraphy shows coherency at time slice 796 m/s and C-wave stratigraphy shows coherency at time slice 1964 m/s at the same inline coordinate and crossline coordinates of 10,400 to 10470. At inline

cordinate 2800 and crossline coordinate 10,650, P-wave stratigraphy shows coherency at time slice 792 ms and C-wave stratigraphy shows coherency at time slice 1968 ms.

The P and C wave are capable of imaging different stratal surfaces because P and C modes have different reflectivities at impedance boundaries. It was observed that it is possible for either P or C mode to have a zero , or near-zero reflectivity at a given stratal geologic surface while the other mode has a large reflectivity.

EXPERIMENTAL

The analysis was carried out on PCs, utilizing the software provided by the Seismic Micro-Technology, Inc; (SMT).
The main service software package provided by Seismic Micro-Technology, Inc; (SMT) include 2d/3dPAK data interpretation, 2d/3d Seismic Interpretation, The Kingdom Suite SynPAK, The Kingdom Suite VuPAK, The Kingdom Suite TracePAK, The Kingdom Suite ModPAK , and the EarthPAK.

RESULTS AND DISCUSSION

Conventional seismic stratigraphy is one of the major traditional tools used to detect the internal complexities and heterogeneities within oil reservoirs. But the concepts and principles of conventional seismic stratigraphy are based only on P-wave seismic data, with little or no applications of S-wave seismic data to reservoir characterization. The complete understanding of reservoir characterization can be achieved only by expanding the principles and concepts of conventional seismic stratigraphy to a new approach described as vector-wavefield seismic data in which geologic systems are interpreted using both P-wave and shear (S) wave (both fast-S, and slow-S data) images of the subsurface sequences. This is so, because, sometimes spatially coincident P and S seismic profiles do not show the same reflection sequences or the same lateral variations in seismic facies character. This observation leads to the conclusion that in complex geologic systems, the sedimentary record must be described by one set of P-wave seismic sequences (and facies) and also by a second, distinct set of S-wave seismic sequences (and facies). Figure 1 shows full-elastic, multicomponent seismic wavefield in a homogeneous earth consisting of a compressional mode P and two shear modes, SV and SH. The propagation procedures of these modes differ as indicated in figure 1. Note that each mode travels through the earth in a different direction along its propagation path.

Laboratory studies of P-wave velocity (Vp) and S-wave velocity (Vs) in cores have shown that the ratio Vp/Vs has a distinct value for different types of rocks. Also, these Vp/Vs ratios are consistent over a wide range of porosities and confining pressures, whereas, each velocity (Vp or Vs) varies when either porosity or confining pressure changes. Thus the combination of P and S seismic data provides a capability to identify subsurface distributions of rock types through Vp/Vs ratios that is not available from P-wave seismic data alone. Particularly important is the phenomenon that S-wave split into fast-S and slow-S components when they encounter strata that are highly anisotropic. This petrophysical sensitivity has been utilized to detect and map fractured rocks with surface-recorded S-wave reflection data. P-waves exhibit little sensitivity to anisotropic rock properties, compared to the sensitivity of S-waves. Thus, 9-component seismic data allow seismic stratigraphy concepts to be expanded into anisotropic rocks where conventional P-wave-based seismic stratigraphy does not apply, or applies in a limited, and weak fashion.

The 3-D, 9-component data used in the study were recorded using midpoint imaging concepts that are standard practice in the oil and gas industry. Three orthogonal vibrators used to generate 9C (9-component) VSP (vertical seismic profile) are vertical vibrator, inline horizontal vibrator and crossline horizontal vibrator (figure 2).
The geometry of the three orthogonal vibrators created stacking bins measuring 110 ft x 82.5 ft across the image space, with a stacking fold of 20 to 24 in the full-fold area of each data acquisition grid. The recording template that moved across the image space consisted of six parallel receiver lines, each spanning 96 receiver stations. Three-component geophones were deployed at each receiver station of this 3-D grid. Each receiver string deployed at a receiver station contained three 3-C geophones, and all three geophones were positioned in an area spanning 3 to 5 feet to form a point array. The geophones were planted carefully to position one horizontal element in the inline direction (the direction that the receiver line was oriented) and the second horizontal element in the crossline direction.

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Analysis of data shows that P and C waves often image different stratal surfaces.The propagation of incident full-elastic seismic wavefield generates four different wave modes, P-wave, SH-wave (horizontal shear wave), SV-wave (vertical shear wave) and C-wave (converted shear wave) as shown in figure 4. These four wave modes reflect independent stratal surfaces. SH, SV, and C are three independent shear wave seismic modes. An upgoing SH mode can be produced by only a downgoing SH mode. The upgoing and downgoing modes are called SH-SH (SH down and SH up). SV is also called SV-SV, meaning SV down and SV up. C is a converted shear wave, meaning it is a special SV mode created by a downgoing P-wave. This is called P-SV, meaning P down and SV up.

Futher imaging differences between P and S-wave modes are illustrated by elastic wavefield stratigraphy (figures 5 through 10 and 14 through 24).
Coherency numerically measures lateral similarity of reflection waveforms in a defined data window. If the wavelet reflecting from an extensive interface has the same waveshape across the image space, the lateral coherency is high. On the other hand, if that interface is cut by a channel or incisement, for instance, the reflecting wavelet changes its waveshape at the edges of the channel. In such a case, lateral coherency is low across those narrow parts of the image space where the channel edges are. In a map of coherency, channels and incisements are shown as trends of low lateral wavelet coherency. At inline cordinate 2800 and crossline coordinate 10,650, both P and C modes show similar but not identical cross section of the incisement at each time-slice coordinate (figure 5). The white line across each seismic section indicates the position of the time slice in each data volume that is used in the image displays; the vertical black bars mark the edge of the incised feature. In figure 6 the P-wave data no longer have a distinct character, while C-wave data has a prominent characteristic. In figure 7, P-wave shows a complex system of overlapping, meandering channels but in figure 8, C-wave shows only one channel. Figure 9 compares both the P- wave and C-wave images.

Basic physics of P-wave and S-wave indicates different reflection behaviors and further shows that P-wave and S-wave do not produce identical images of stratal surfaces This is expressed mathematically as shown below:

REFLECTIVITY PARAMETERS

Layer (i) $(P_i,\ V_{p,i}\ ,\ V_{s,i}\ +1)$

Layer (i +1) $(P_{i+1},\ V_{p,\ i+1},\ V_{s,\ i+1})$

P AND S REFLECTION COEFFICIENTS

$$R_{i,s} = \frac{(PV_s)_{i+1} - (PV_s)_i}{(PV_s)_{i+1} + (PV_s)_i} \qquad R_{i,p} = \frac{(PV_p)_{i+1} - (PV_p)_i}{(PV_p)_{i+1} + (PV_p)_{i+1}}$$

$$R_{i,s} = \frac{Bi\,(1 - R_{i,p}) - (1 + R_{i,p})}{B_i(1 - R_{i,p}) + (1 + R_{i,p})} \qquad B_i = \frac{(V_p/V_s)_i +1}{(V_p/V_s)_i}$$

These mathematical forms can be graphically expressed to relate P-wave reflectivity ($R_{i,p}$) to S-wave reflectivity ($R_{i,s}$) (figure 10). B_i is the horizontal axis. V_p is the P-wave velocity, V_s, the S-wave velocity, i is the upper geologic sequence, while i +1 is the underlying geologic sequence. The P-wave reflection coefficient ($R_{i,p}$) is the constant for each curve and the value is expressed on each curve. The curves show that if the P-wave reflection coefficient ($R_{i,p}$) is zero at any given geologic interface, the S-wave reflection coefficient can be zero, negative or positive, depending on the value of B_i. On the other hand, if the reflection coefficient of S-wave is zero at any given geologic boundary, the P-wave reflection coefficient may be zero, negative or positive, depending on the value of B_i.

This implies that full science of reservoir characterization can be achieved by incorporating the principles and applications of vector-wave field seismic data in which geologic systems are interpreted using both P-wave and shear (S) wave images of subsurface stratigraphy.

CONCLUSION

Since conventional seismic stratigraphy is limited when characterizing oil resevoirs because its concepts and principles have been developed and demonstrated using only P-wave seismic data, and at the same time have been verified using only P-wave technology; the complete science of reservoir characterization can be realized only by expanding its principles and applications to vector-wavefield seismic data in which geologic systems are interpreted using both P-wave and S-wave images of geologic sequences. This statement is based on the results of this study which showed that in some instances, spatially coincident P and S seismic profiles do not exhibit the same reflection sequences or the same lateral variations in seismic facies character. It is further concluded that in a complex geologic environment, it is necessary that sedimentary record be described by one set of P-wave seismic sequences(and facies) and also by a second, distinct set of S-wave seismic sequences (and facies). A full comprehension of geologic environment (reservoir architecture and heterogeneities) cannot be made until both P and S wave images are unified in seismic stratigraphy interpretations. The application of both P and S wave images to oil reservoir characterization is the current trend in most oil and gas companies and will sooner or later overtake the conventional seismic stratigraphy of only the P-wave imaging.

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LIST OF ACRONYMS AND ABBREVIATIONS

C-wave:	**Converted wave. A reflected SV shear wavefield produced by P- to -SV mode conversions when a downgoing P-wave propagates through a series of interfaces.**
9C:	**9-component**
P-wave:	**Compressional mode of a seismic wavefield.**
S-wave:	**Any shear mode (C, SH or SV)**
SH:	**Horizontal shear wave**
SMT:	**Seismic Micro-Technology**
V_p:	**P-wave velocity**
Vs:	**S-wave velocity**
VSP:	**Vertical seismic profile**
SV:	**Vertical shear wave**

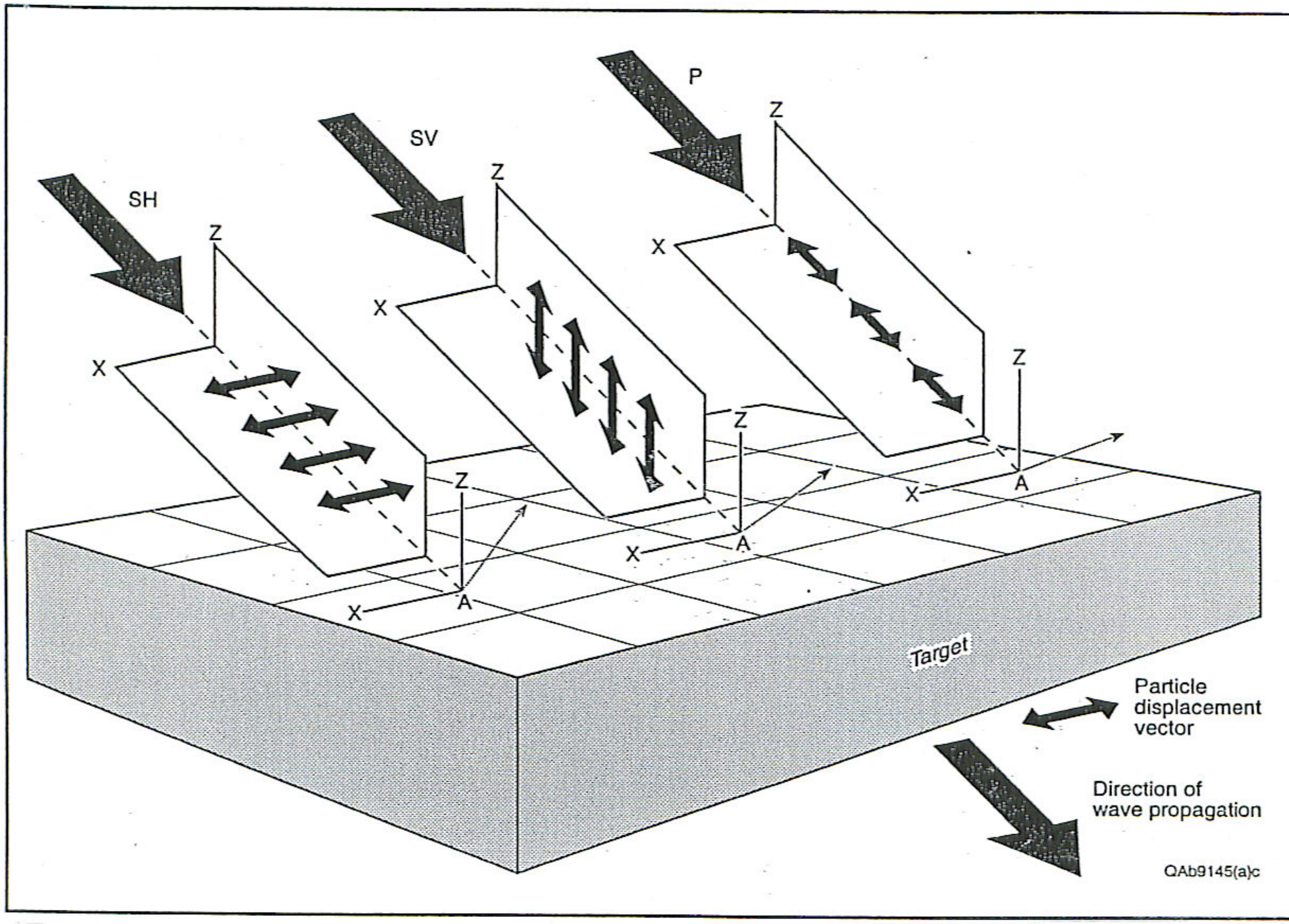

Figure 1. Propagation of the three fundamental modes, P, SH, and SV that comprise vector-wavefield seismic data.

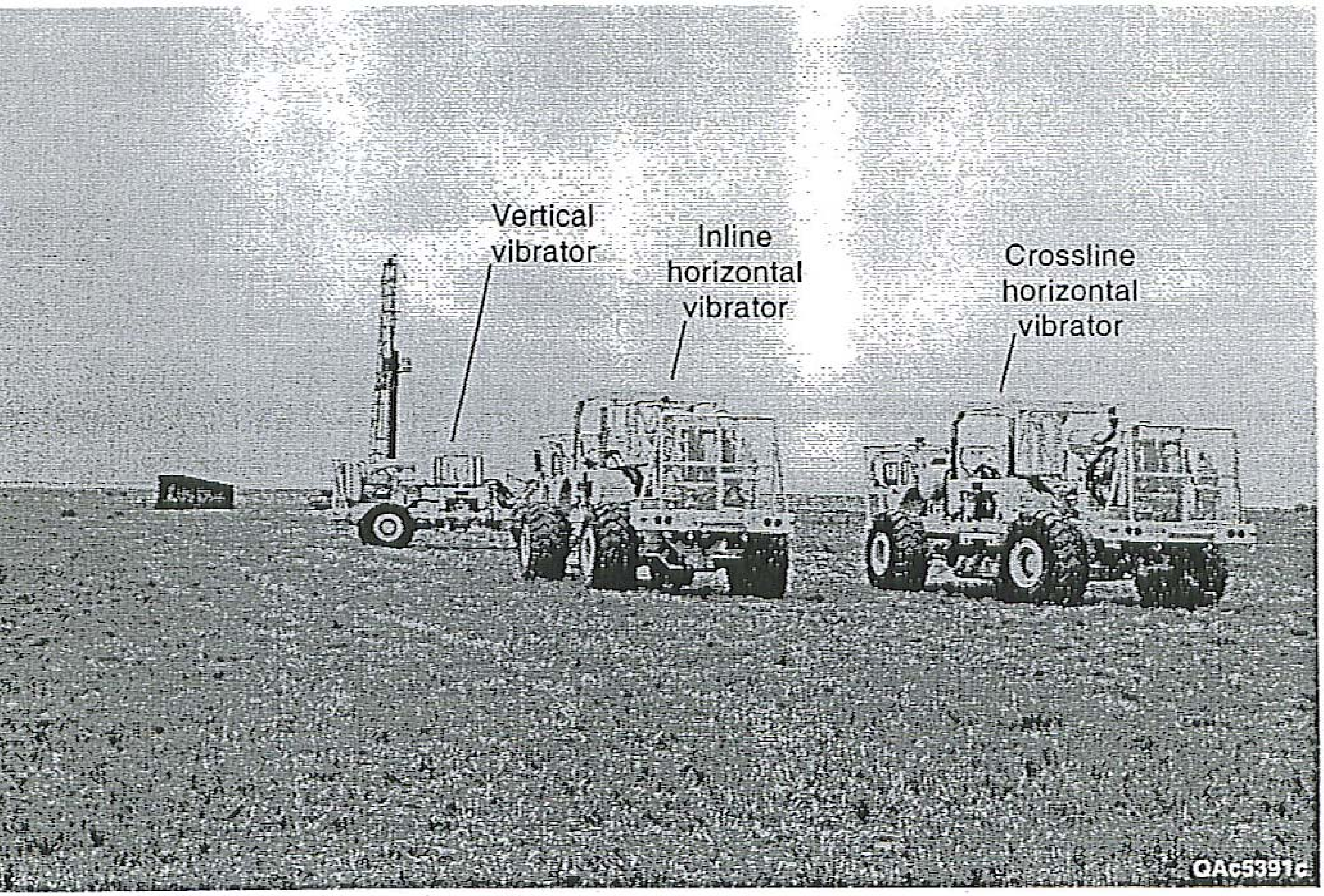

Figure 2. Orthogonal Vibrators used to generate 9C (9-component) VSP (Vertical Siesmic Profile).

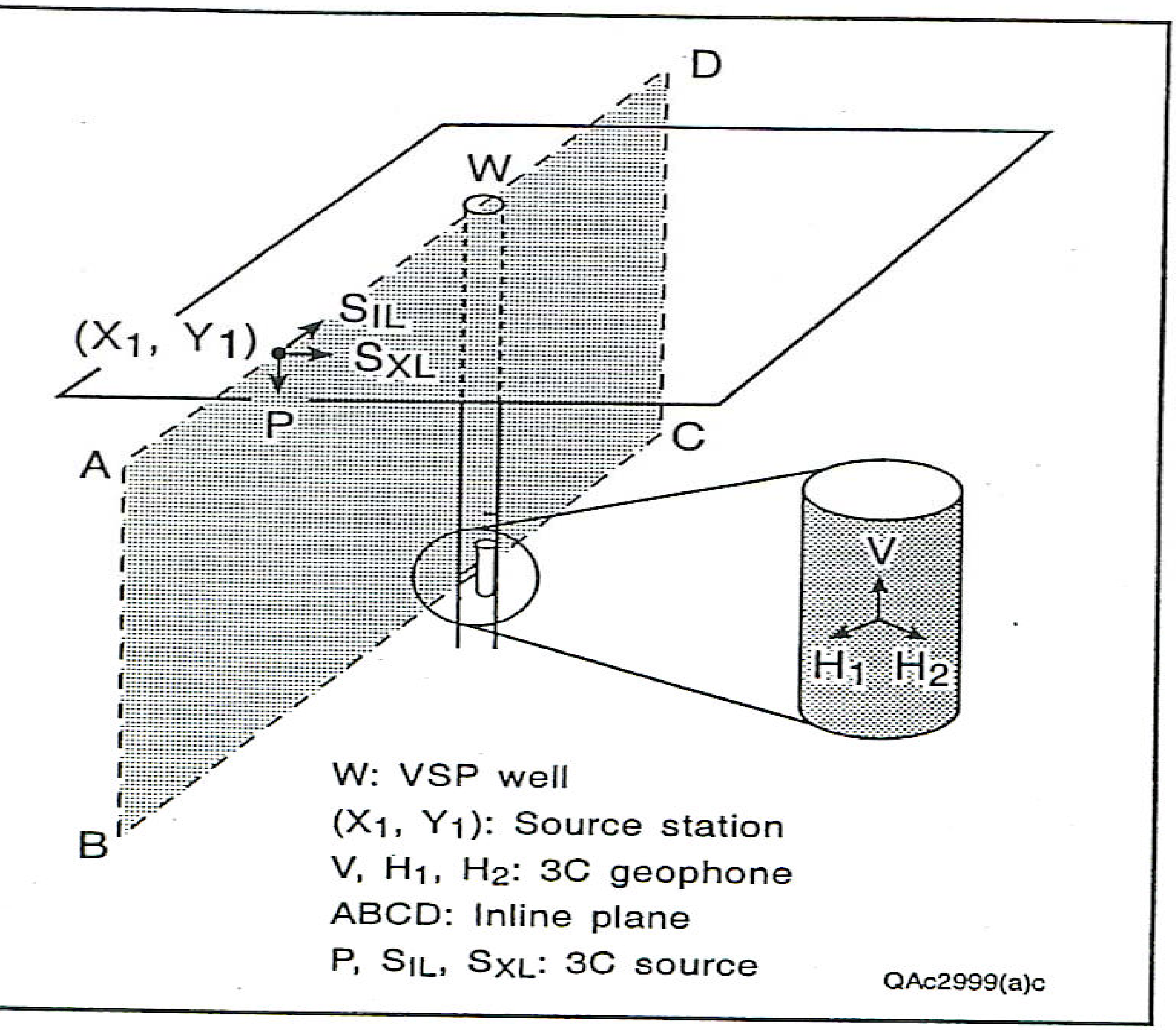

Figure 3. Fundamental geometry and key elements needed for 9C VSP data acquisition.

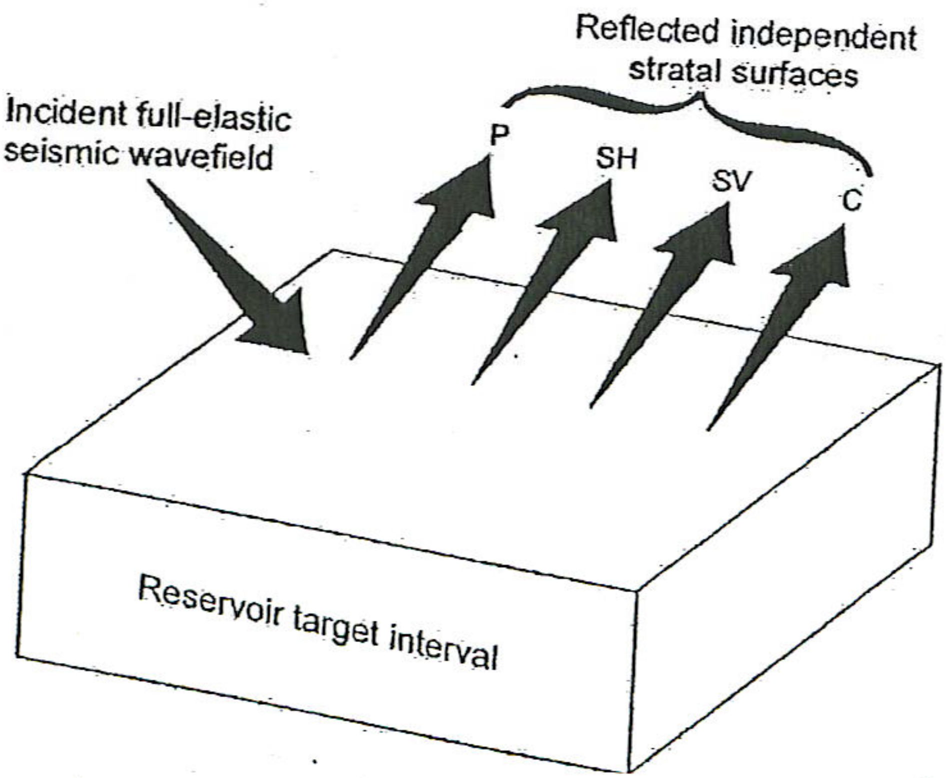

Figure 4. Comparison of conventional seismic stratigraphy and elastic-wavefield seismic stratigraphy. Conventional seismic stratigraphy utilizes only reflected P-wave modes. Elastic-wavefield seismic stratigraphy utilizes all elastic modes P, SH, SV, and C.

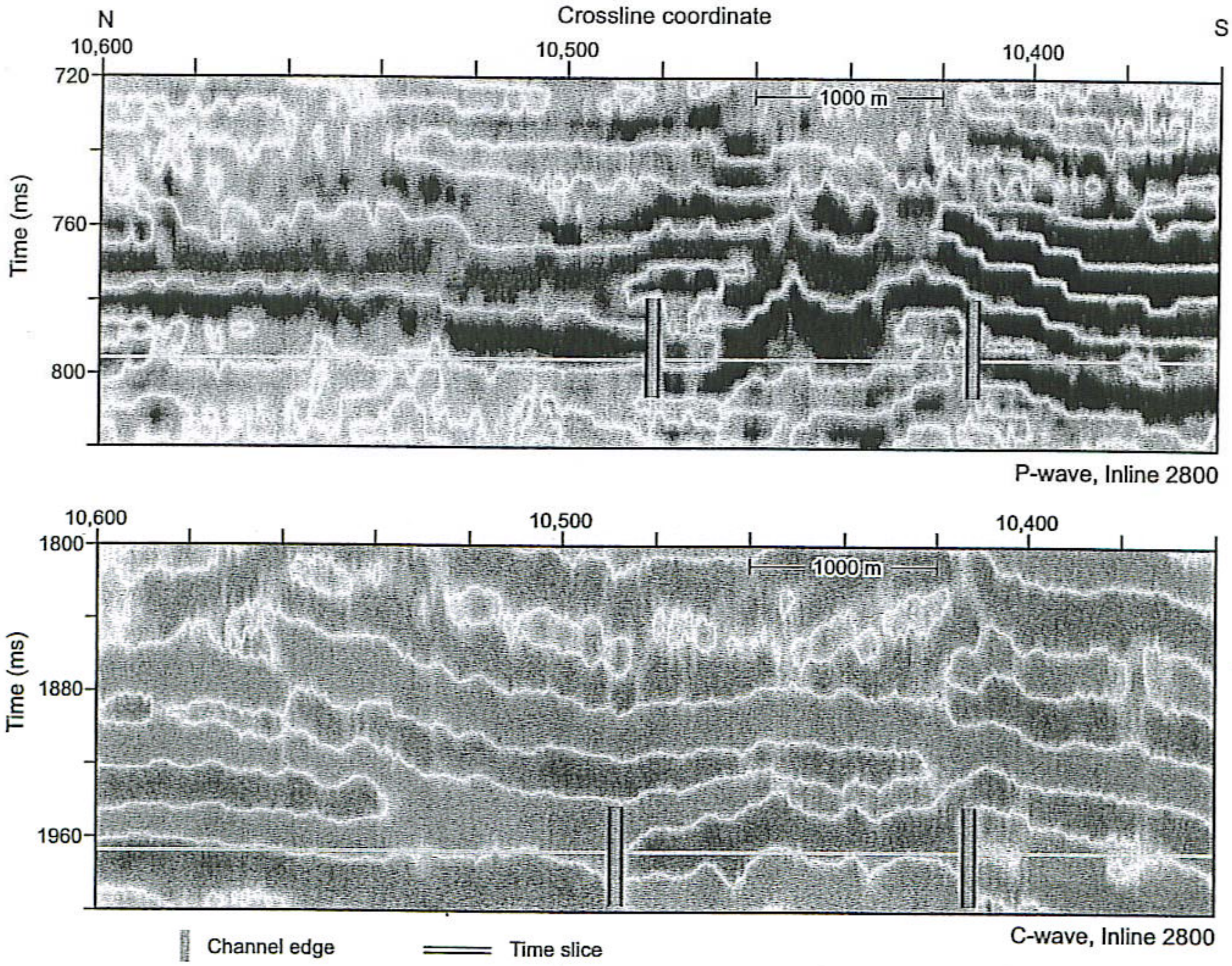

Figure 5. Inline profile 2800 across image target

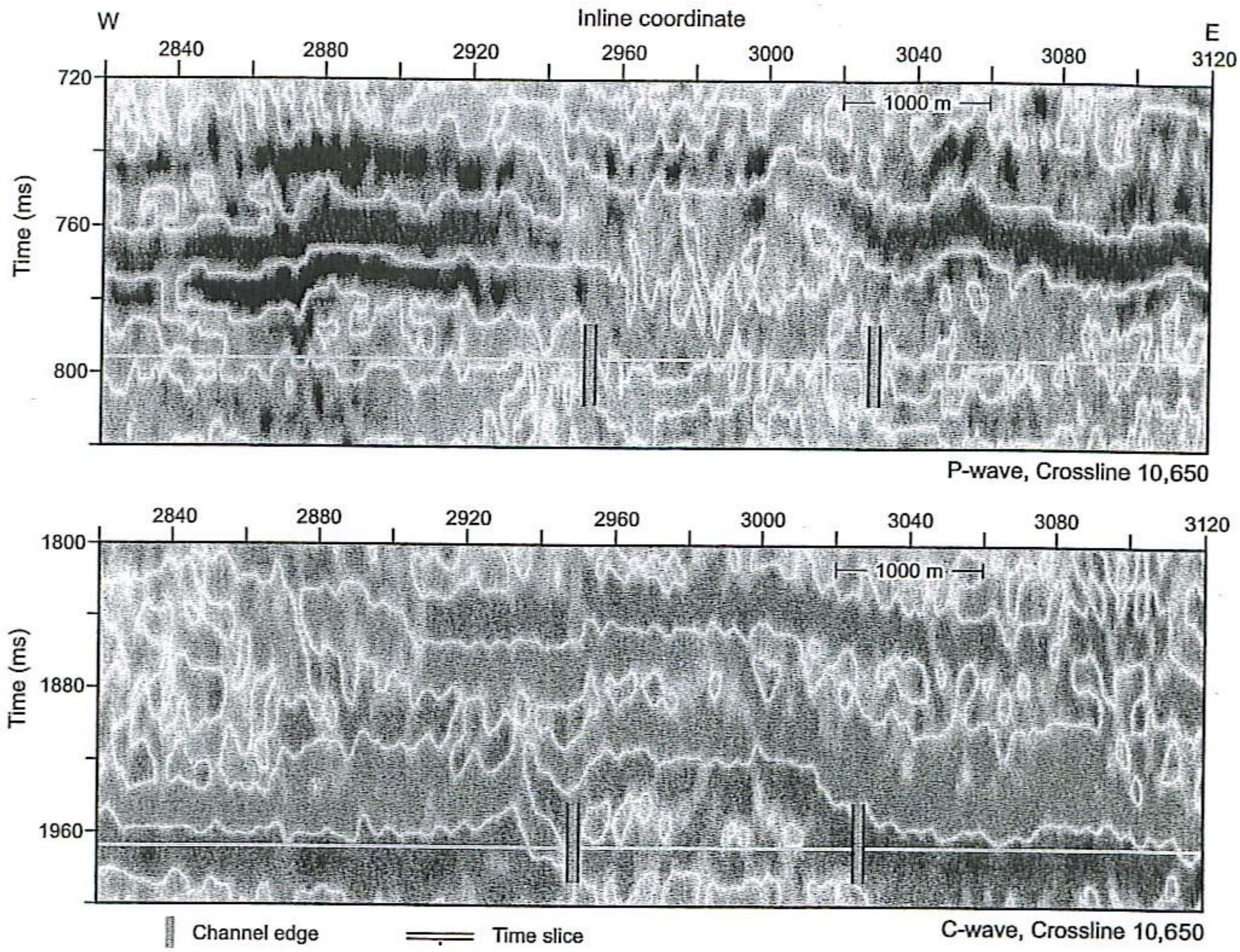

Figure 6. Crossline profile 10,650 across image target

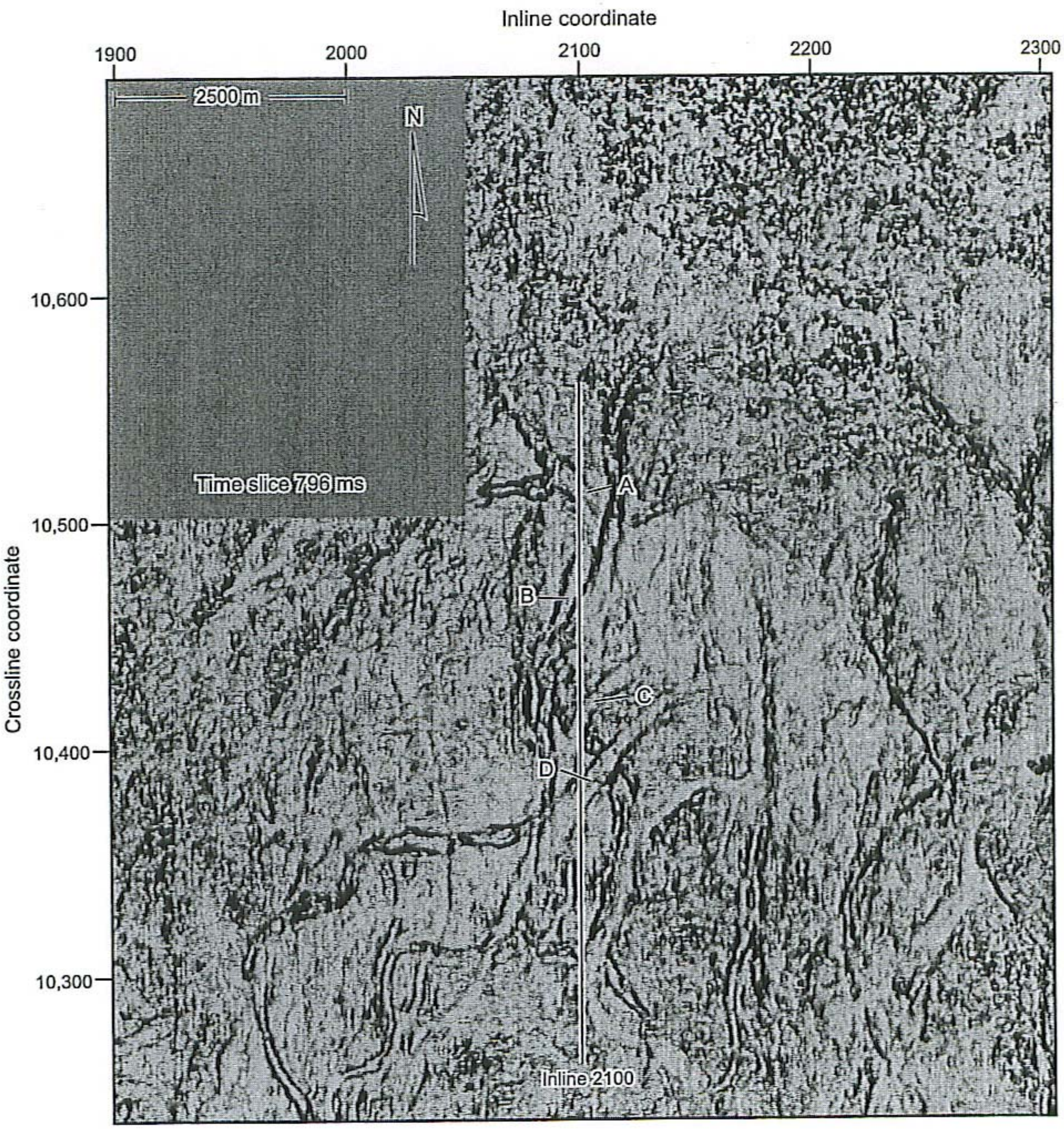

Figure 7. P-wave image search target

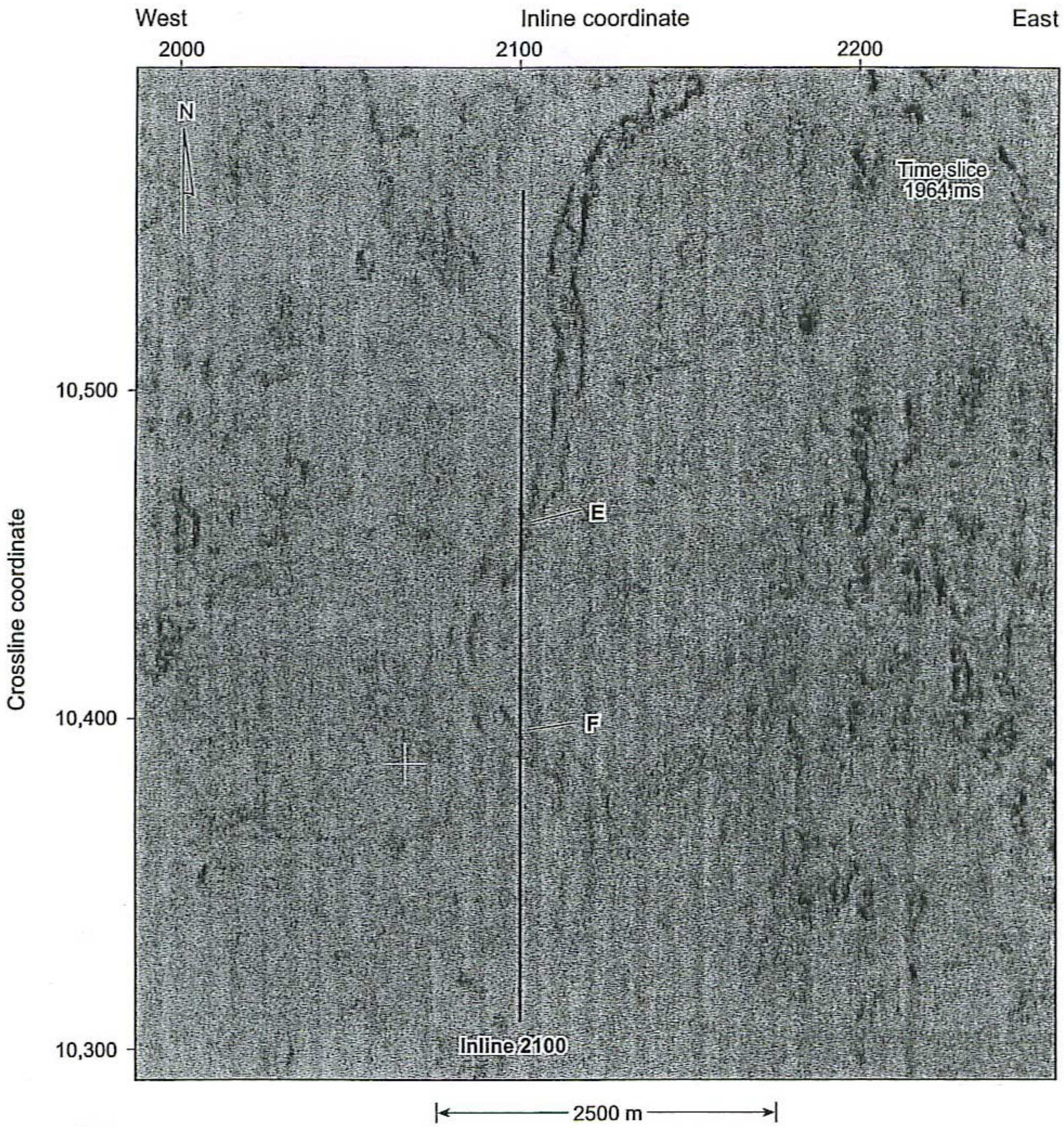

Figure 8. Depth-equivalent C-wave target

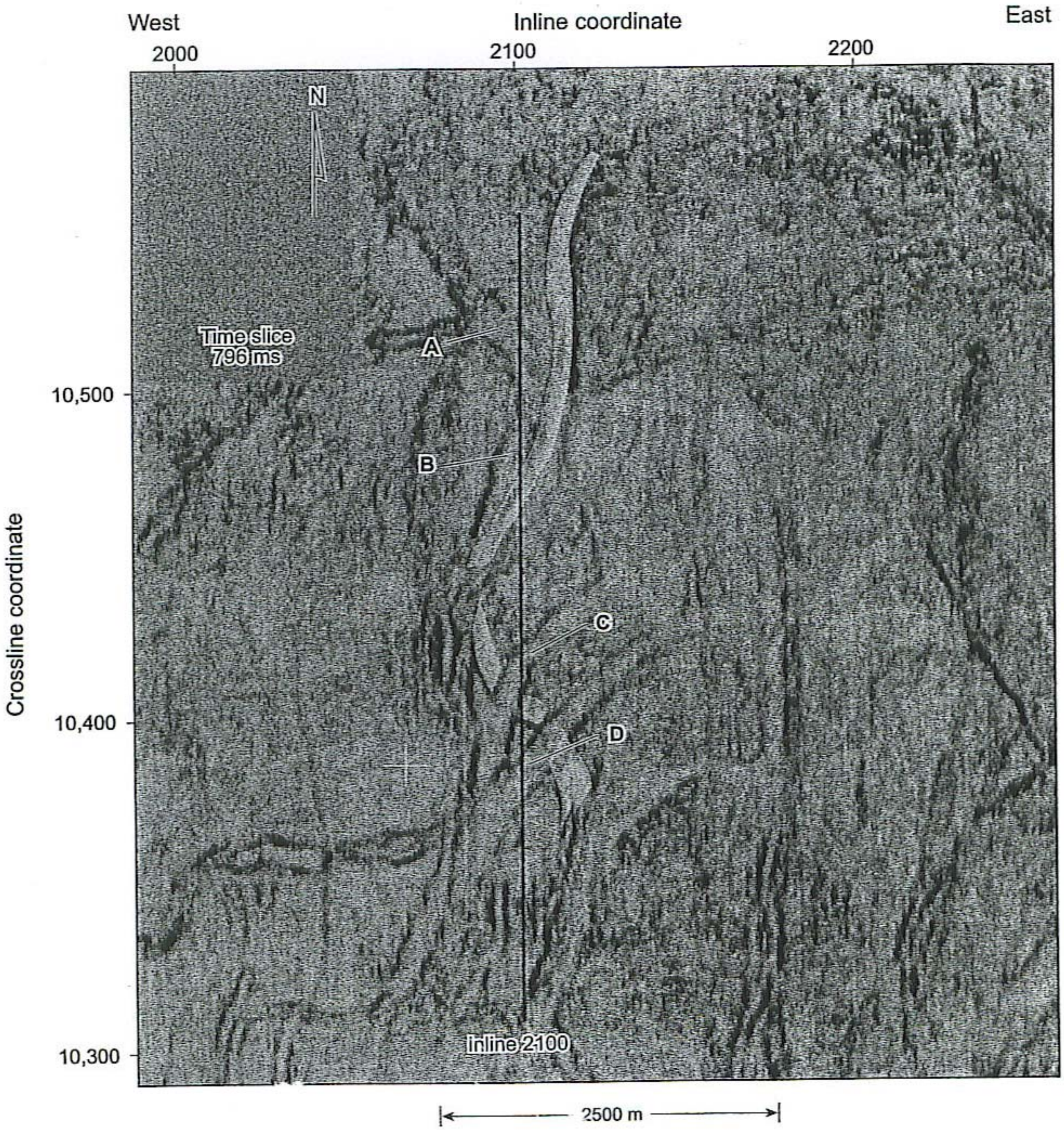

Figure 9. Comparison of P-wave and C-wave image targets.

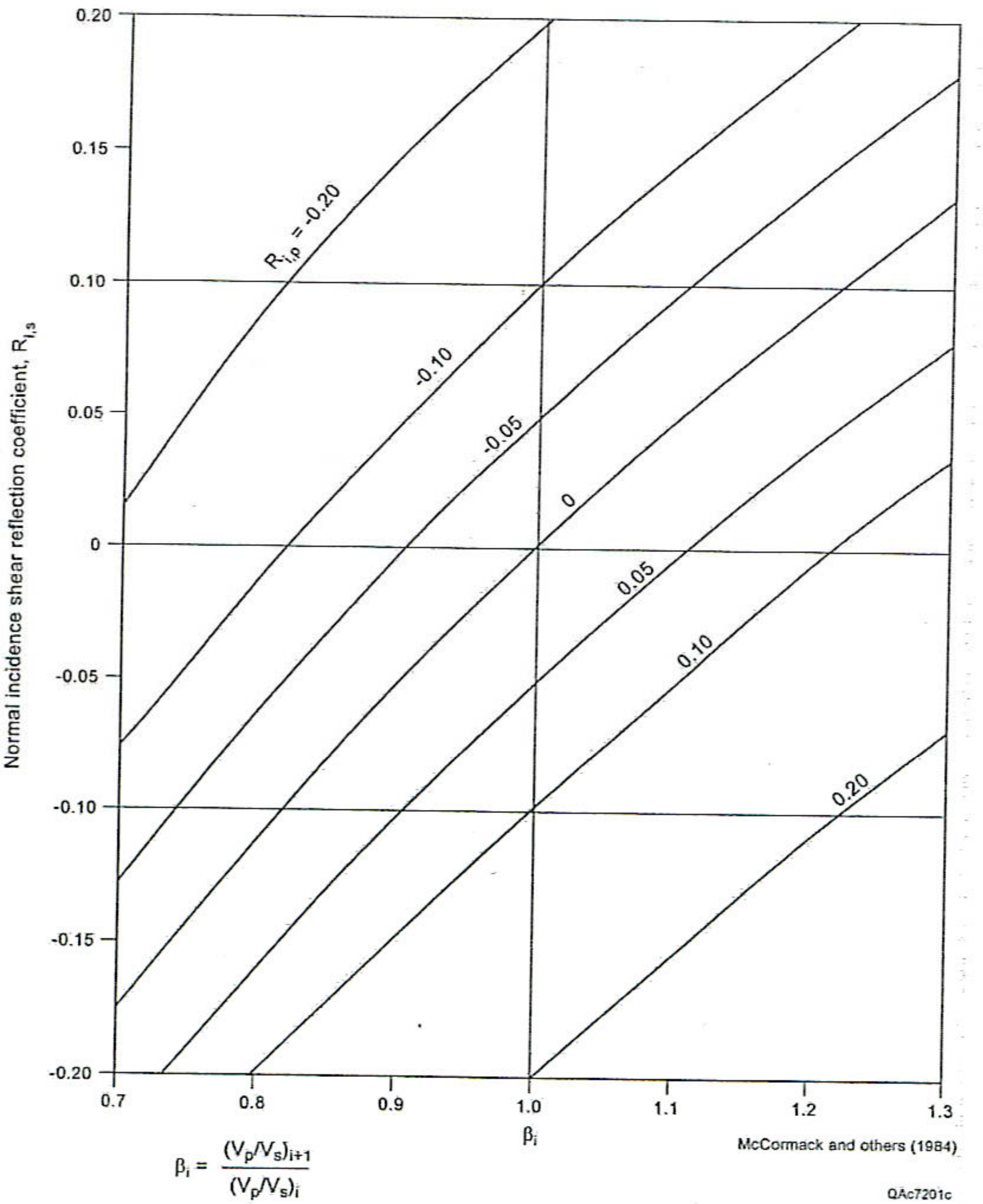

Figure 10.Contrast between P reflectivity $R_{i,p}$ and S reflectivity $R_{i,s}$ for vertical incidence on a stratal surface.

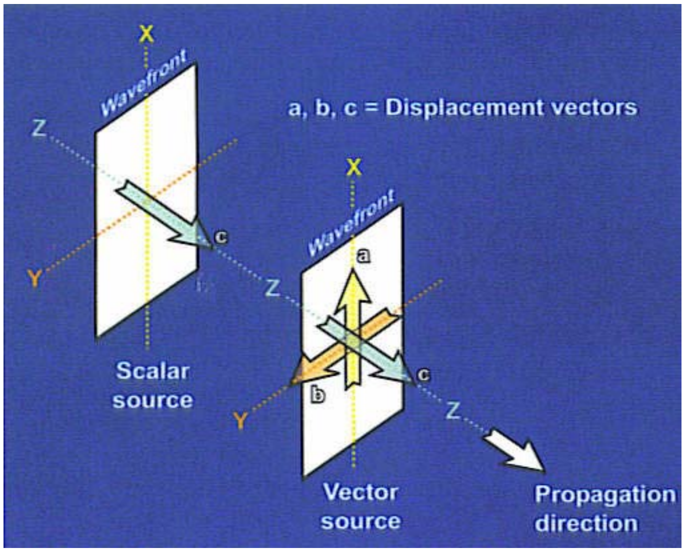

Figure. 11. Scalar-source Seismic Wave Mode

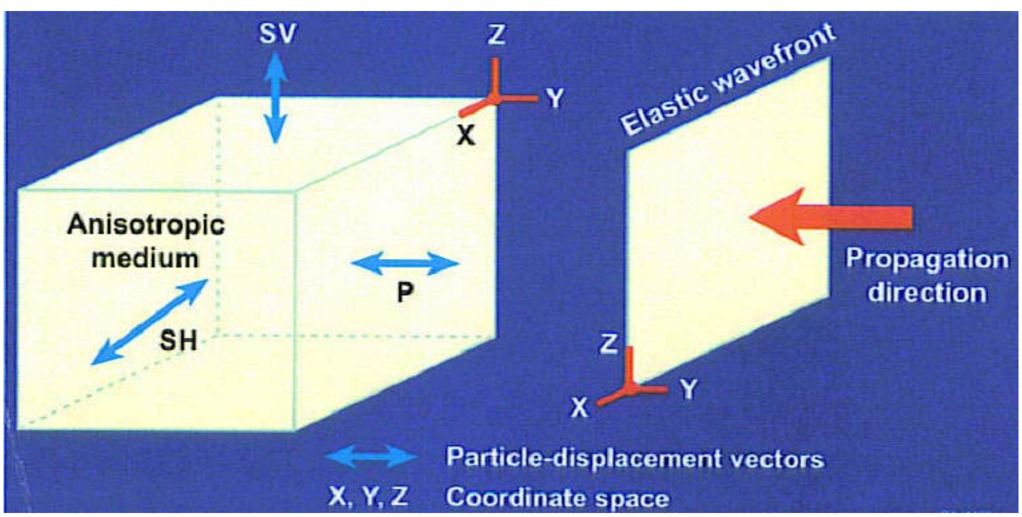

Figure 12. Orthogonal Displacement Vectors (P, SV,SH) Associated with Multicomponent Seismic Wavefields

Data-acquisition option	Captured mode(s)
9-C	P-P, P-SV, SV-SV, SV-P, SH-SH
6-C	P-P, P-SV, SH-SH
4-C	P-P, P-SV
3-C	P-P, P-SV
1-C	P-P

Data-acquisition option	Captured mode(s)
9-C	P-P, P-SV_1, P-SV_2, SV_1-SV_1, SV_2-SV_2 SV_1-P, SV_2-P, SH_1-SH_1, SH_2-SH_2
6-C	P-P, P-SV_1, P-SV_2, SH_1-SH_1, SH_2-SH_2
4-C	P-P, P-SV_1, P-SV_2
3-C	P-P, P-SV_1, P-SV_2
1-C	P-P

Figure 13. Wave Modes Associated with Different Types of Multicomponent Seismic Data

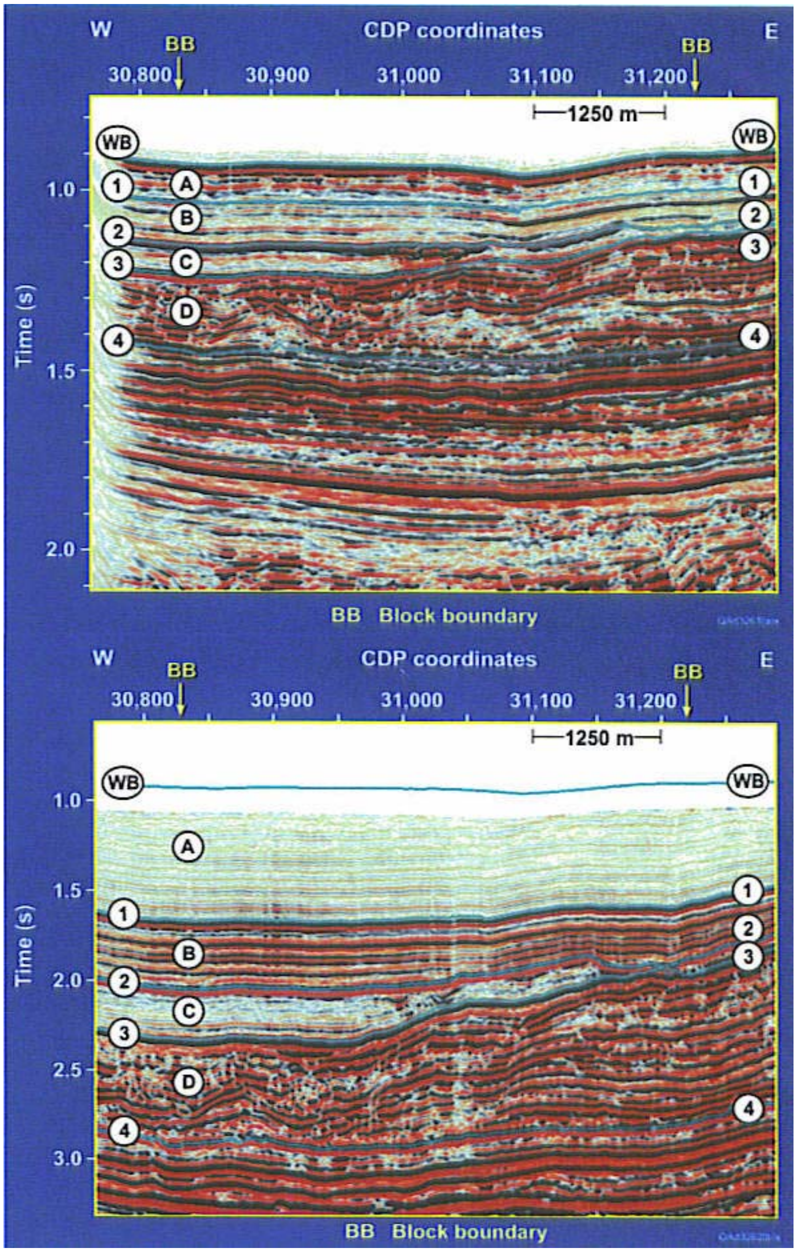

Figure 14. Comparison Between P-P and P-SV Elastic-Wavefield Seismic Stratigraphy

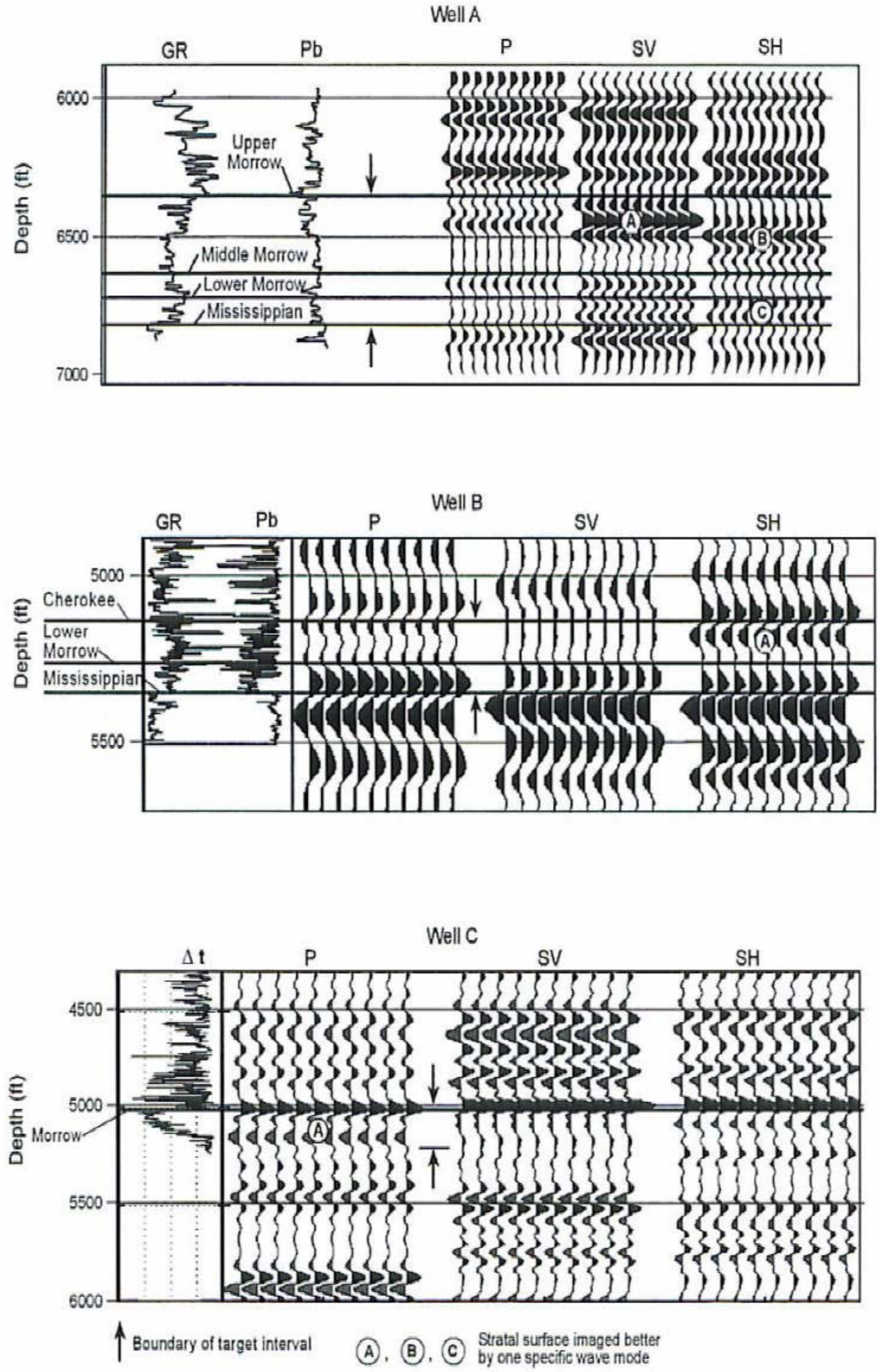

Figure 15. Depth-based P-P, SV-SV, and SH-SH Images From 9-C VSP Data From Three Wells

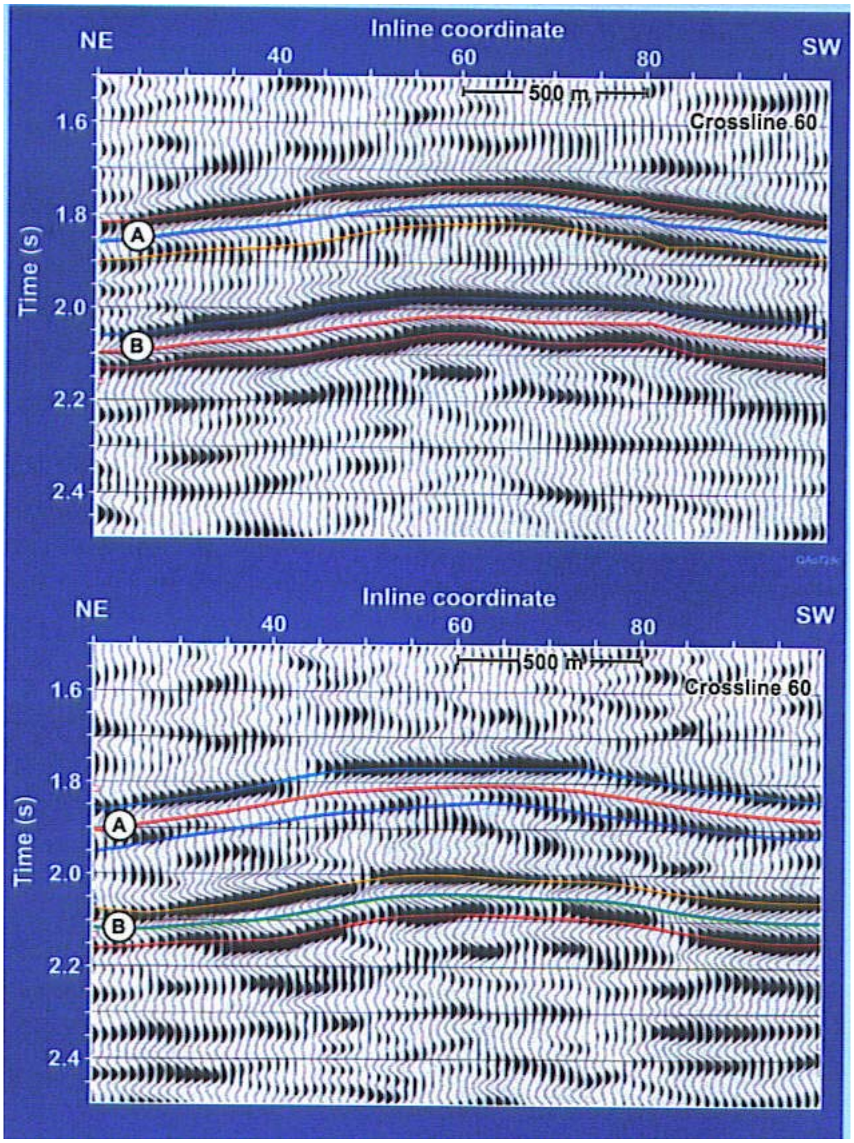

Figure 16. Comparison Between fast-S and slow-S Images.

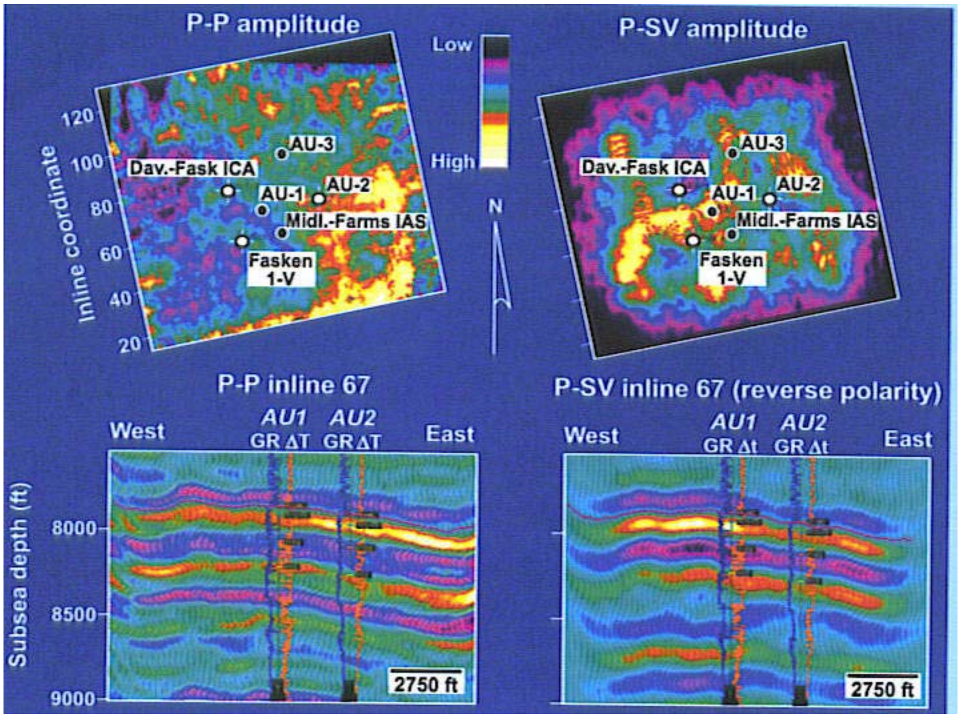

Figure 17. Comparison Between P-P and P-SV Modes

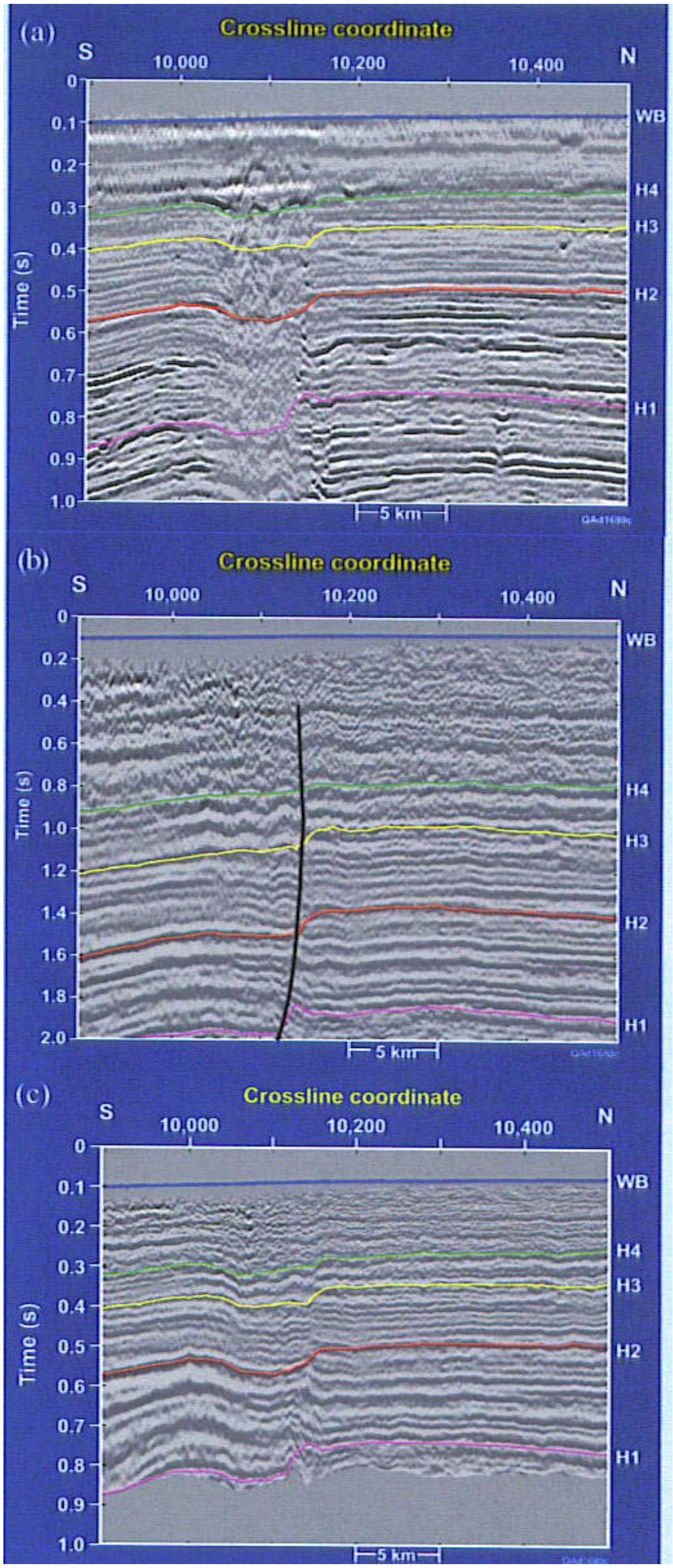

Figure 18. P-P and P-SV Images from 4C3D Multicomponent Data

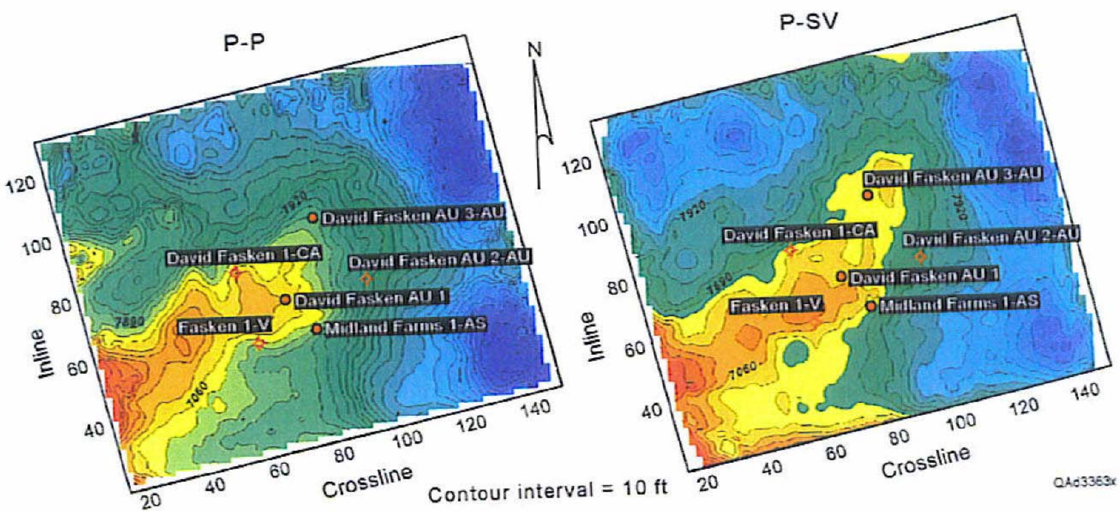

Figure 19. Structural Features of P-P and P-SV Data

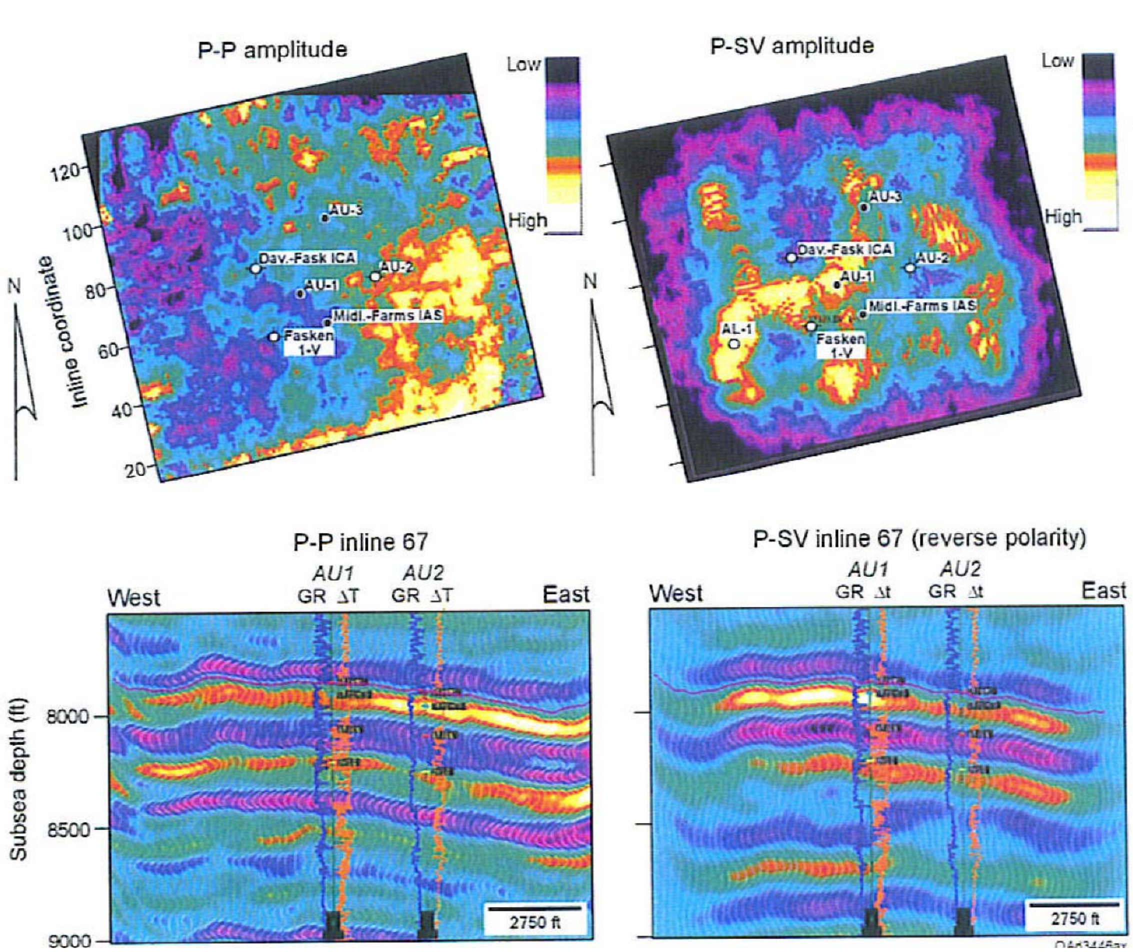

Figure 20. Maps of P-P and P-SV Amplitude-based Seismic Facies

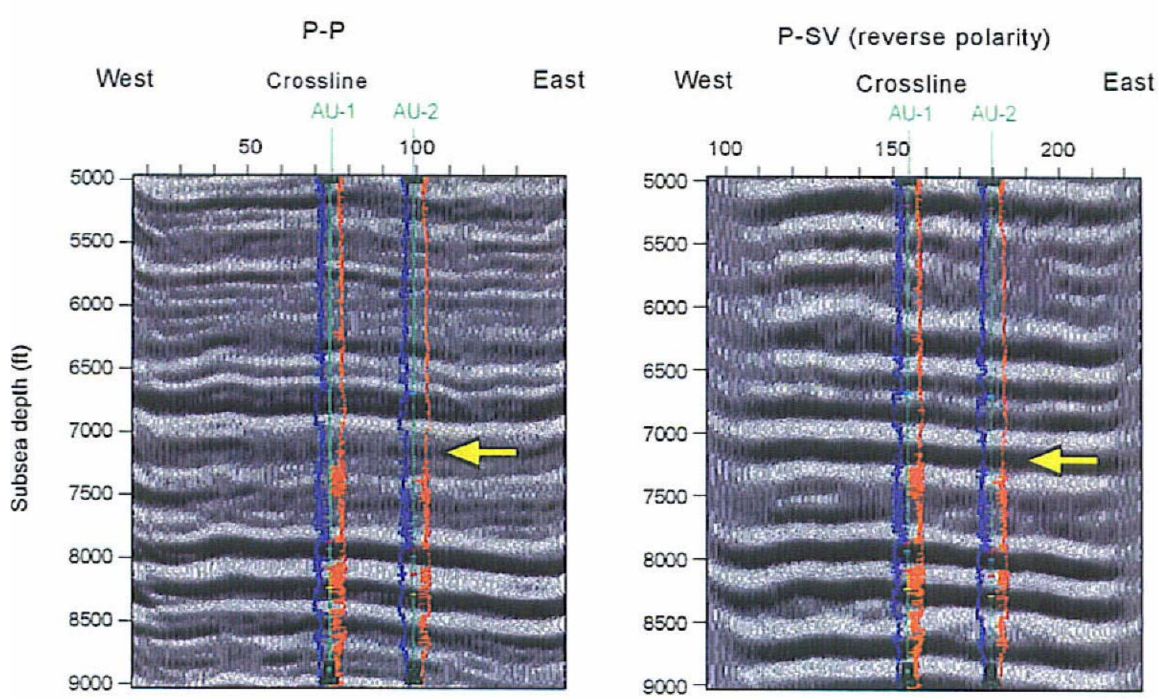

Figure 21. P-P and P-SV Images

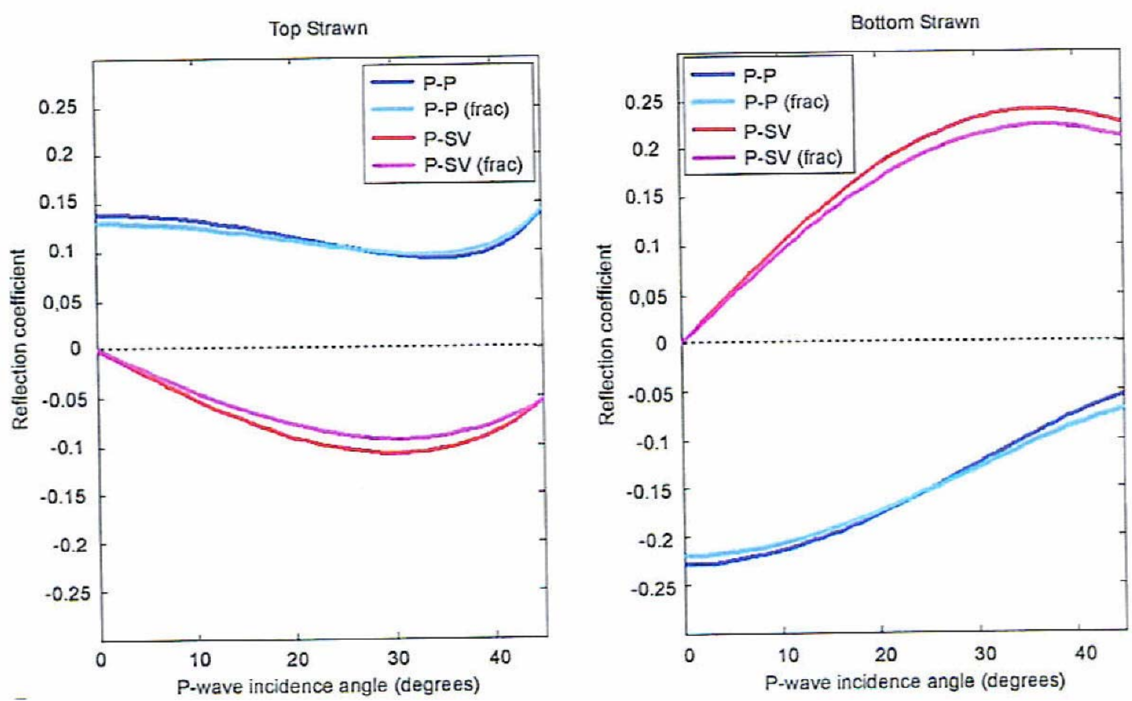

Figure 22. Effect of Isoptopic Fracturing on P-P and P-SV Reflectivities

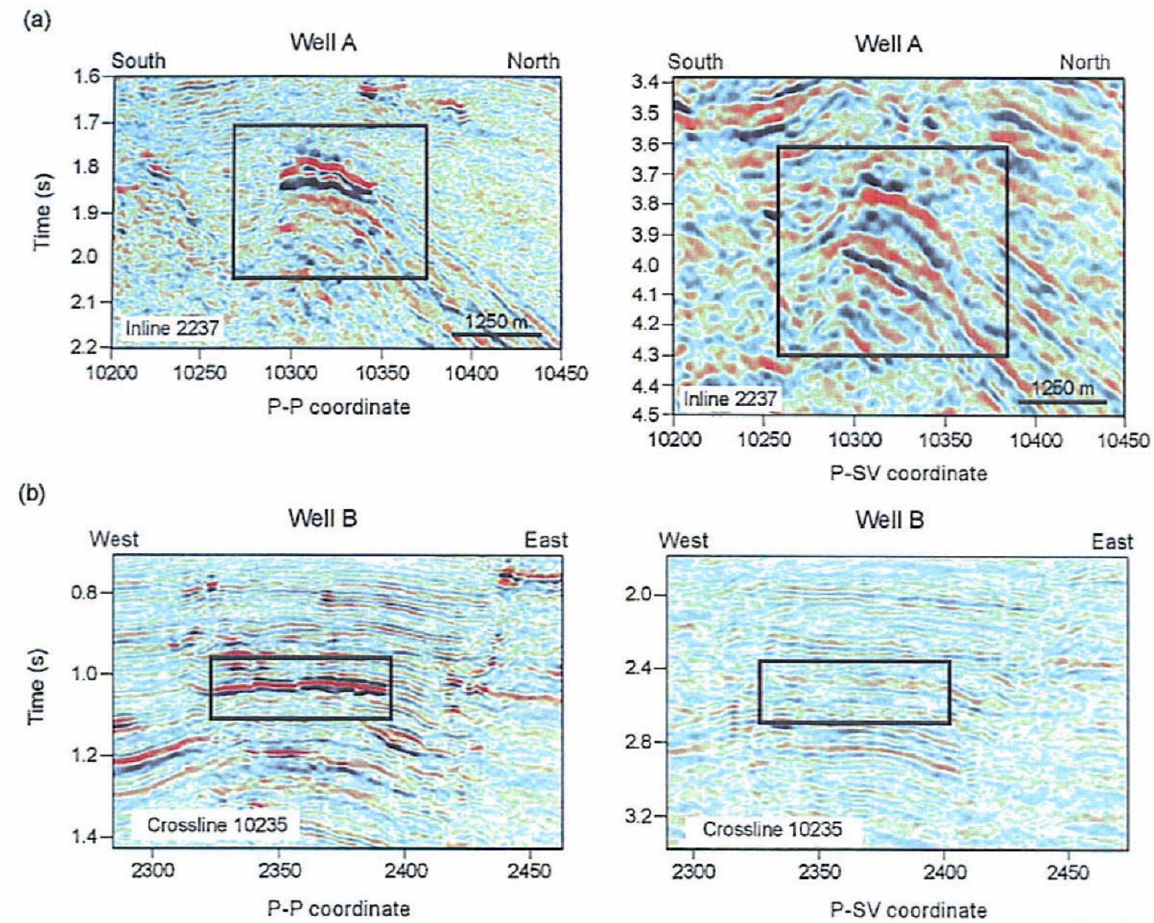

Figure 23. Comparisons of P-P and P-SV Reflectivities

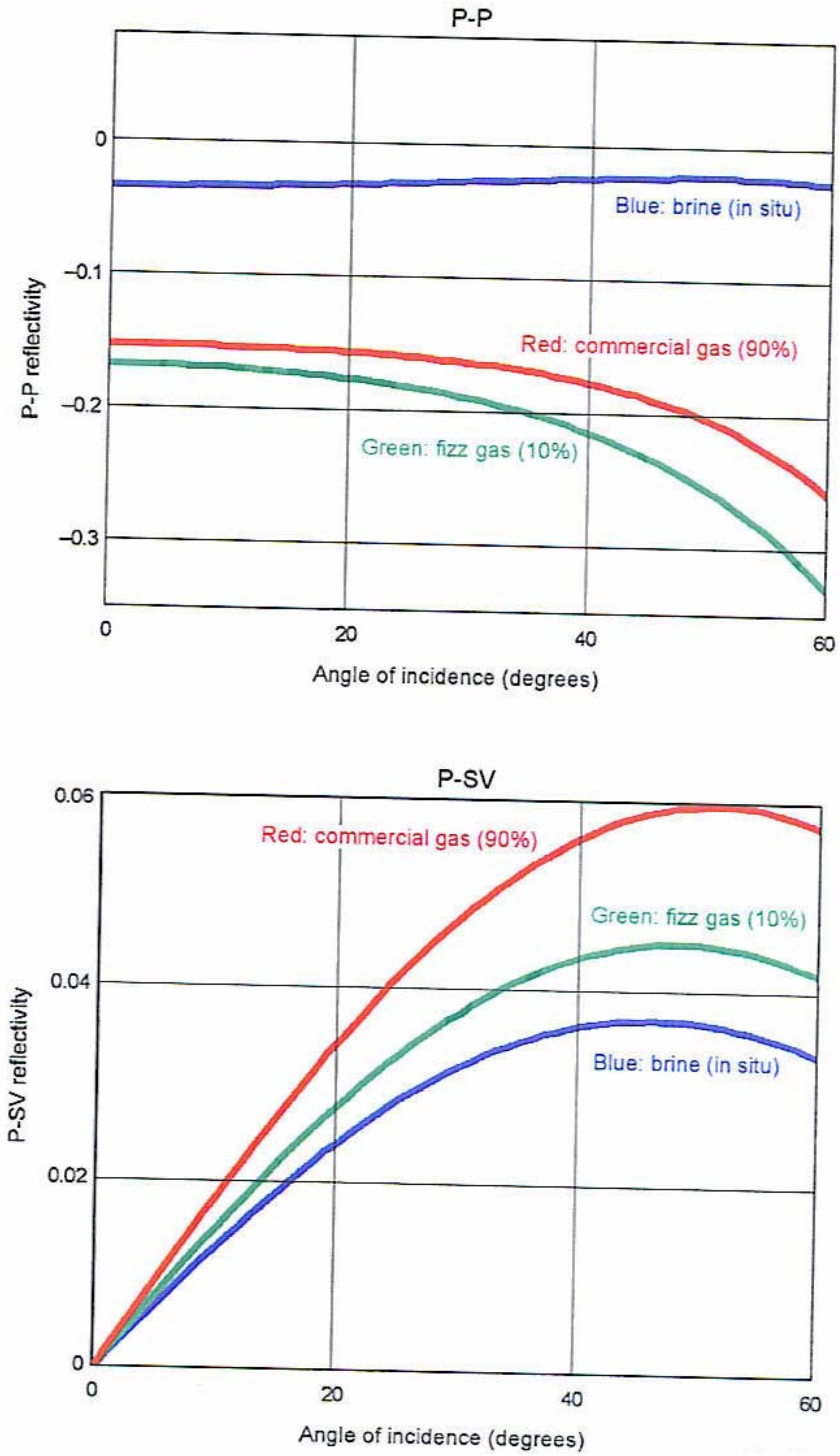

Figure 24. Comparisons of P-P and P-SV Modes