The present and promise of P-S seismic exploration

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ABSTRACT

Use of converted waves (P-S) in exploration geophysics began in the early 1980's. In the last several years, P-S surveying has developed rapidly. Recent special processes for S-wave analysis include shear statics, asymmetric binning, shifted hyperbolic velocity analysis, P-S DMO, pre- and post-stack migration, and shear seislog inversion. Numerous applications for P-S sections have arisen including sand/shale differentiation, anisotropy analysis, imaging through gas zones, and AVO analysis. Converted waves hold enormous promise for marine surveys and land 3C-3D problems.

BACKGROUND

Real seismic sources generate a great richness of wave types. These waves propagate through the Earth creating a further abundance of other waves by scattering, refracting, converting, and reflecting along the way. P-to-S conversions are one of the dominant types of mode changes. This is both a nuisance and an opportunity. The nuisance has been well described - "Nearly all seismic exploration is carried out with P-waves, S-waves merely contributing to the noise (Sheriff and Geldart, 1982)." This may have been true, in the past, using only vertical motion recordings, acoustic assumptions, and lack of experience with shear waves. However, the opportunity in such events is now becoming much more clear and compelling. Many of these promising concepts will be discussed in this paper. Sheriff and Geldart's (1982) comment really alludes to the lack of adequate recording, analysis, and use of shear waves. We interpret it as a challenge to understand and extract more information from the full recorded seismic wavefield.

So, by using three-component (3-C) receivers - that is by listening a little harder - we can completely record this abundant seismic wavefield from conventional sources. The additional records provide an opportunity to not only make other sections but to discriminate more effectively against undesirable events. Let's reflect on what we are ultimately attempting to do in seismic exploration and generally how we go about doing so:

> What are we trying to do in seismic exploration?
>
> > Create a 3-D depth image of rock type, structure, and saturant.
>
> And how?
>
> > By using advanced surface seismic surveys and combining them with geologic models, borehole measurements, and other information and imagination.

Where does 3-C analysis fit into this methodology? Perhaps we can look at what have been identified as seismic industry trends:

- 2D → 3D
- reflectivity → rock properties
- time → depth
- isolated → integrated
- post-stack → pre-stack
- acoustic → elastic
- isotropic → anisotropic

Three-component measurements are a part of several of these trends. From the top, the change from 2-D to 3-D analysis makes the seismic picture more realistic and complete. The signal-to-noise ratio can be considerably improved by gathering data from an areal array not a linear one. Then converting seismic reflectivity in time to correspond to rock properties in depth is a major goal of processing and interpretation. This means integrating other information with the seismic events to convert them to pseudo-logs in depth. Handling the seismic records before stacking means that more information can be extracted, but we have to understand the actual trace amplitudes better. This really means understanding the elastic, anisotropic nature of the earth. Further indications of these trends in seismology are shown in Figure 1.

Ultimately, we would like to have images that are geological cross-sections showing rock type and pore saturants. We are unlikely to be able to do this from P waves alone. This is because different rocks and saturants have the same P-wave response. Thus we need additional types of data to try to constrain the rock type and fluids therein. The S-wave properties along with the P-wave properties can help characterize the rock. A schematic diagram of this procedure is shown in Figure 2. We can obtain S-wave properties from the analysis of 3-C data such as shown in Figure 3. Knowing the P-wave velocity as well as the S-wave velocity, for example, can help in the estimation of gas saturation, through the Vp/Vs value (Figure 4). If we do have S-wave velocity and reflectivity, what are they good for?

- imaging interfaces with low P-wave contrast
- giving an additional image with different reflectivity, tuning, multiples
- augmenting conventional AVO analysis
- investigating anisotropy
- calibrating P-wave bright spots
- vector filtering and side-scanning
- using Vp/Vs for lithology
- imaging through gas chimneys

3-C SURVEYS IN TWO DIMENSIONS

A full nine-component survey has a 3-C source and a 3-C receiver (see Figure 5). The diagonal elements shown in the chart have received the most attention. Historically, there was more interest, in the shear-wave world, in the pure shear (S-S) events. This may have occurred because the pure S section (SH-SH or SV-SV) was easier to analyse with its symmetric ray paths. These raypaths were immediately amenable to analysis with standard seismic processing procedures (CMP binning, hyperbolic velocity analysis, acoustic approximations). Pure S surveys have had some very nice successes. A number of authors (e.g., Ensley, 1984; Tatham, 1985) presented detailed histories on the use of S-S events. However, shear-wave sources were required, survey costs were high, and the resultant S sections were often poor in comparison to their P-wave counterparts. On the whole, this lack of clear, consistent success has led to lessened interest in S-S surveying.

On the other hand, less expensive surveys were undertaken that used conventional P-wave sources, but horizontal in addition to vertical receivers. In this case, source-generated P waves propagate into the earth, hit a boundary at non-normal incidence, and partially convert into S waves. There are a number of advantages of converted-wave surveys over pure-shear surveys. Converted-wave surveying:

- uses conventional P sources
- can record a P-wave survey simultaneously
- requires a shorter data recording time
- has only one-way propagation through the near surface (less attenuation - thus higher frequency - and smaller total static)

Thus, there are strong technical, logistical, and economic reasons to prefer P-S surveys over S-S surveys. Again, we record P-S waves largely on the radial channel (the horizontal geophone element that is pointing in the direction of line shooting). From the waves recorded, a converted-wave section can be made.

Converted waves were known early on in seismology through the Zoeppritz equations in 1919 and before. But, surprisingly little work on P-SV waves is reported in exploration seismology before the early 1980's. Converted waves (P-S) had several obvious problems. Perhaps most importantly, the reflection raypath is asymmetric - the S-wave leg up had a different angle of reflection than the P-wave angle of incidence down. This leads to a skewed propagation trajectory (see Figure 6). Conventional P-wave processing algorithms are now inappropriate. Furthermore the SV and P waves continue to couple, potentially giving very complicated records. But bad as all of this is, P-S waves can be recorded and analysed with a little extra effort. A full set of sections, corresponding to the modes in Figure 5, is shown in Figure 7.

On land, source effort is a major factor in expenditures. Sources, whether they be dynamite, vertical vibrator, Omnipulse, or S-wave vibrator are expensive. Therefore we generally want to minimize our source effort. Receiver channels are relatively inexpensive. Therefore listening harder (recording 3-C instead of vertical only) is fairly cheap. One apparent limitation, at this time, is getting enough 3-C geophones: They are in significant demand and short supply.

One of the earliest discussions of the analysis and interpretation of converted waves was published by Garotta et al. (1985). Data analysed in this paper were recorded by a two-component geophone (biphone). It consisted of one vertical and one horizontal element (usually in the radial or in-line direction). Raw data from the biphone are shown in Figure 8. The biphone was an interesting instrument, but there are several disadvantages to the biphone arrangement:

- 3-D geology can give off-line energy (data in the transverse direction)
- 2-D lines may not be straight (energy in the transverse direction)
- poor plants may leave the geophone rotated
- anisotropy can rotate waves out of the shooting plane
- the full vector motion may be necessary for analysis

Thus full 3-C recording is recommended. Lawton and Bertram (1993) tested four 3-C geophones, using a source at various azimuths to the receivers (Figure 9). They found that all of the geophones tested performed well except the Omniphone (which is now off the market). This was important to further establish the fidelity of the field measurements before proceeding on to sophisticated processing.

Processing P-SV data

Several authors presented analysis of the asymmetric reflection point trajectory (Fromm et al., 1985; Chung and Corrigan, 1985) and its importance in P-S imaging. Garotta (1985) outlined procedures for handling P-S data and presented additional interpretive uses for the data. Stewart (1991) extended Chung and Corrigan's (1985) work to describe converted waves where the source and receiver had unequal elevations (Figures 10 and 11). This and other work on binning led to the creation of further P-SV sections. One such data set from Carrot Creek, Alberta is shown in Figure 12. However, some artifact began to be visible in the P-SV sections. Eaton and Lawton (1992) analysed the fold of P-SV sections and found it to be highly oscillatory under certain conditions - the source interval is an even integer of the receiver spacing (Figure 13). They recommended odd-spacing configurations or additional processes such as adjacent trace averaging or DMO.

Also because of the very low S velocity in the near surface, receiver statics in the P-S survey can be very large. Lawton (1990) gave numbers of about 70 ms for the receiver static. Cary and Eaton (1993) found receiver statics of 100 ms They also derived a new method of calculating these statics using trace-to-trace coherence. The near surface has a marked influence on the P-SV data by large and variable statics. But, the near surface has another undesirable effect: attenuation. We know that in the subsurface P-P and P-SV events have about the same frequency content (Geis et al., 1990). However by the time the P-SV events are recorded at the surface their frequency has decreased relative to the P wave's (Eaton et al., 1991). This remains a limitation of surface P-SV analysis (Figure 14).

In carrying the analysis of P-SV waves further, Slotboom (1990) considered the velocity analysis problem. He derived a shifted hyperbola equation for NMO correction that can correct the offset traveltimes better than a normal hyperbolic velocity analysis. After NMO, it is important to understand the Fresnel zone (or the averaging aperture in a stacked section) and the potential of P-SV data to be migrated. Eaton et al. (1991) derived the P-SV Fresnel zone and found that for the same frequencies, the P-SV Fresnel radius is smaller than the corresponding P-P case. However, with the lower P-SV frequencies often observed at the surface P-P and P-SV radii work out to be about the same. They also showed that P-SV data could be migrated post-stack. Harrison and Stewart (1993) considered the migration problem further and derived a P-SV migration velocity for a layered material (Figures 15, 16, 17). Harrison (1992) also developed an equation and procedure for DMO correction of converted wave data. Stewart (1991) also derived a method for converting S-wave reflectivity to a shear-velocity log. This method is similar to the Seislog method of Lindseth (1979).

Interpreting P-S data

Geis et al. (1990) used 3-C VSP measurements to estimate seismic velocities in the subsurface (Figure 18). They also addressed the polarity issue using the Aki and Richards (1980) convention. They found that P-S waves and pure P waves were recorded with the same polarity. They began to use some of the standard methods of interpretation to correlate P-S waves, synthetic seismograms, and logs.

Garotta et al. (1985), as mentioned previously, published one of the earliest papers on the interpretation of P-SV data. This insightful paper processed P-P and P-SV data by analysing vertical and horizontal channels separately with different statics and velocities. Also, the concept of what was later called, "asymptotic binning" was introduced and they produced their final P-SV sections using this gather and binning method (Figure 19). They showed two case histories: Distinguishing on and off a gas sand using Poisson's ratio (derived from tp/ts interval times) and defining a sand/shale lateral variation to delineate an oil-saturated Viking sandstone reservoir (Figure 20 and 21).

Lawton and Howell (1992) developed a P-SV (and P-P) synthetic seismogram program to assist in the correlation and interpretation process. This modeling algorithm uses the offset dependent reflectivity of both P-P and P-SV waves to create synthetic seismograms. These AVO stacks are exceedingly useful in interpretation. Nazar and Lawton (1993) used them to analyse data from the Carrot creek field (Figure 22). The oil-saturated conglomerate in this region is not well imaged by conventional data but is readily apparent on P-SV sections (Figure 23).

Coulombe et al. (1992) also considered AVO effects but in carbonates (Figure 24). They found that P-SV and P-P AVO effects were in evidence and could be modeled. Lawton and Harrison (1993) analysed data from Springbank, Alberta in the Rocky Mountain foothills. The prospective section here has deposits in the Cretaceous and Paleozoic sediments. Synthetic seismograms are very useful in this structural area (Figure 25). Synthetic seismograms are also used in determining Vp/Vs rations in another carbonate play region in Lousana, Alberta (Figures 26 and 27). Miller et al. (1994) found variable Vp/Vs values in this region. The Vp/Vs values in the Cretaceous section (2.2-2.5) are indicative of a clastic section while those in the Paleozoic (1.5-2.0) are characteristic of carbonate rocks. The lower values in the Paleozoic, from shot point 172 to 212, are coincident with an underlying oil-bearing reef. The reef may have had some effect on the subsequent deposition leading to a seismically visible anomaly. Stewart et al. (1993) interpreted crossed P-SV lines and VSP data from the Willesden Green area of Alberta. The survey was designed to find anisotropy in the Second White Speckled shale. The data recorded were excellent and the tie between VSP and surface seismic was very good (Figure 28). However, there was no obvious anisotropy.

The Promise

There is great excitement with the new 3-C marine surveying systems. Using ocean bottom seismometers, all of the land P-SV processes can now be applied to marine cases. Berg et al. (1994) show a preliminary but superlative improvement in imaging a gas reservoir in the North Sea using P-SV data (Figures 29 and 30).

Lawton (1994) discusses the design of 3C-3D surveys. He shows the importance of using source and receiver spacings that are not even multiples of each other. One must carefully consider converted wave design so as to not have lines or regions of low fold. Cary (1994) details the processing flow for P-S waves in a 3-D survey. Finally, Larson and Stewart (1994) have developed interpretation techniques for the analysis of P-S data in 3-D. From one 3C-3D seismic survey come three products: the P-P volume and the anisotropic (P-S1 and P-S2) volumes (Figure 31). We can now develop 3-D Vp/Vs values as well as have two independent sections to compare, contrast, and integrate. 3C-3D seismic measurements may well do for P-S waves what was done for P waves. The frequently lower S/N ratio in 2-D converted wave sections may be made significantly better by 3-D surveys.

The analysis and examples here are concerned with conventional "P-wave" sources and 3-C receivers. Thus the events of major interest are P-S waves. However with the conventional source, S-waves too are often generated at or near the source. Thus the possibility does exist to make pure shear (SV-SV) sections. Also, if these SV source waves do exist then they can convert to P waves, so the SV-P section becomes a possibility too. Also once we have understood these fundamental modes, multiple conversions may be generated. In these cases, we could have say a P-S-P mode say converting through a high-velocity layer. Furthermore, 3-C recordings can be used to make better P-wave sections via modal and directional filters.

The seismic survey has used P waves for many years - and with great success. Is there anything else to do with seismic? Can we analyze P waves any further? Can S waves help solve exploration problems? The answer to these questions is yes. For we always need better resolution in our final sections, higher signal-to-noise ratios, new stratigraphic and structural images, and seismic-based images that give petrophysical information. There's lots left to do with seismic, especially converted waves.

CONCLUSIONS

Converted-wave analysis is presently developing very swiftly using processing and interpretation tools similar to those used in conventional P-P surveying. A number of uses from sand/shale differentiation to imaging through gas are possible. P-S seismic can often augment pure P-wave data and sometimes replace it. Interpreting P-S seismic structure, amplitudes, and its relationship with P-wave data holds a great deal of promise. Expansion into a marine setting with ocean-bottom sensors and 3C-3D recording are the technologies to watch.

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Top Subjects of Reference

(Abstracts at 1993 SEG Meeting)

Modeling	65
3-D	57
Inversion	48
Depth conversion	47
Anisotropy	40
Imaging	36
Interpretation	35

Major Subjects of Interest

(Abstracts at 1994 SEG Meeting)

Imaging	55
Borehole (logs, VSP, xwell)	55
3-D	41
Inversion	30
Velocity analysis	26
3-C	20
Anisotropy	20

FIG. 1. Subjects of interest at recent SEG Meetings.

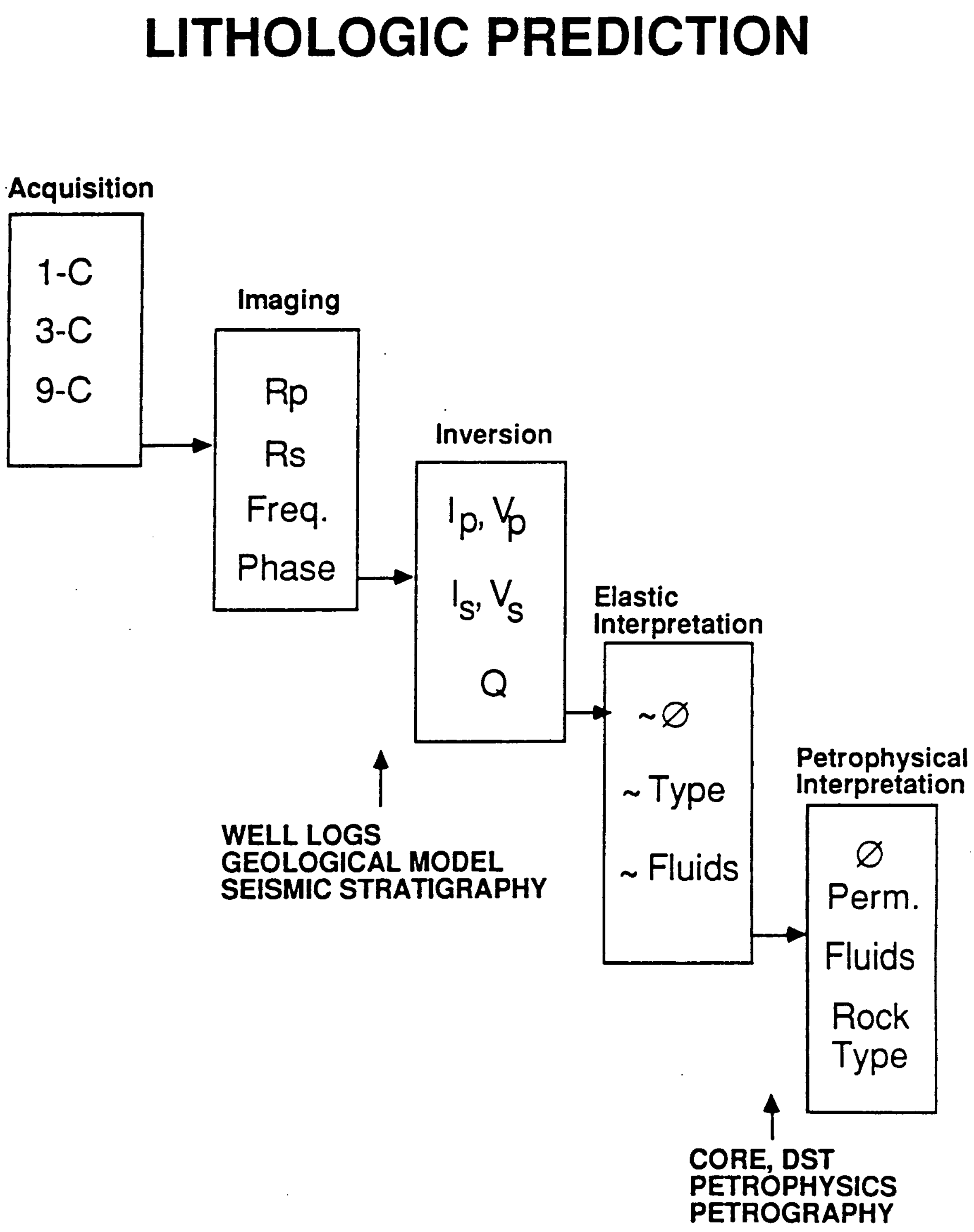


FIG. 2. Data acquisition, imaging, analysis, integration, and interpretation procedure for predicting lithology.

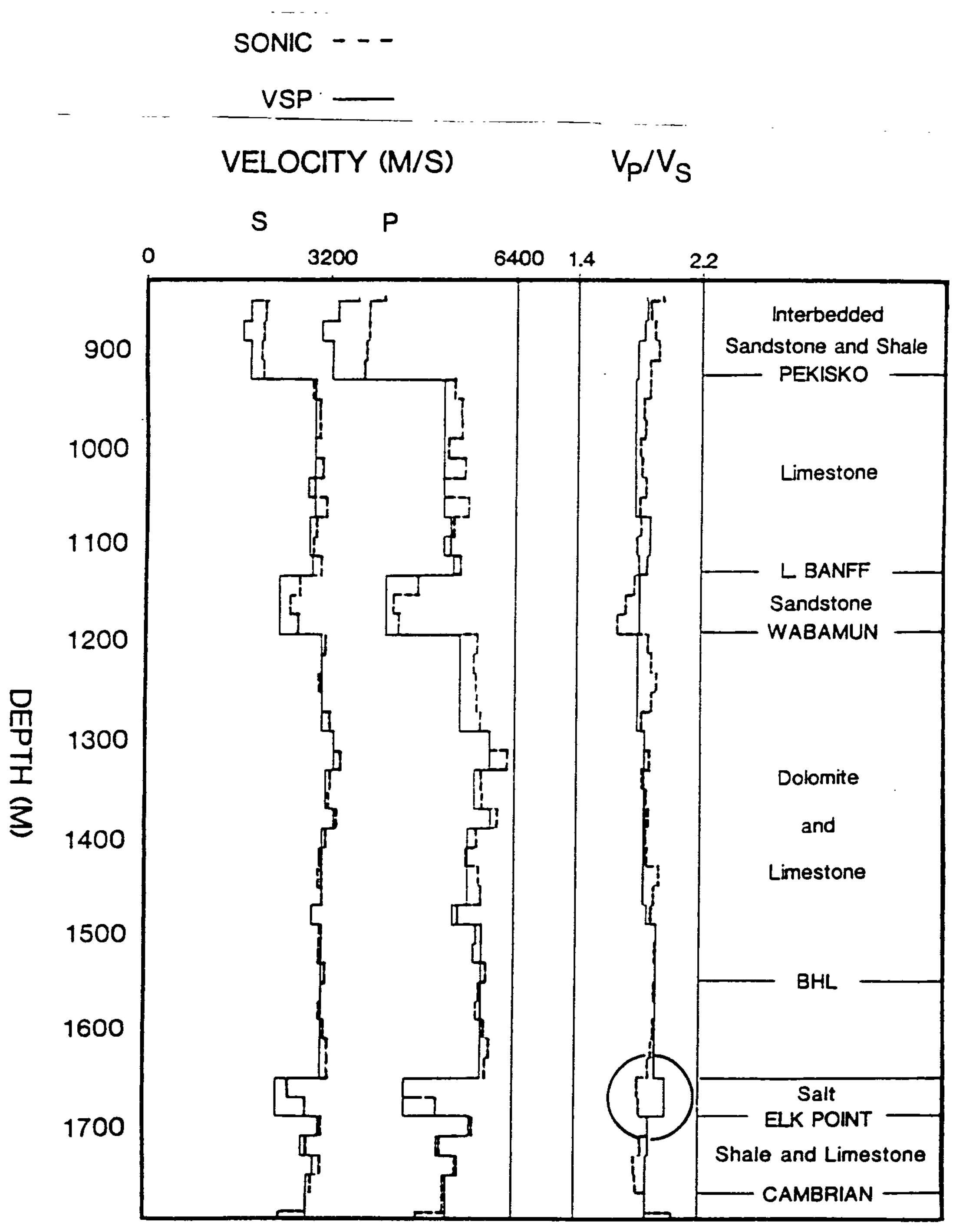


FIG. 3. P and S interval velocities as determined from traveltime inversion of VSP direct arrivals in the Rolling Hills area of Alberta. Sonic log values are also shown for comparison. Vp/Vs values are indicated (Geis et al., 1990).

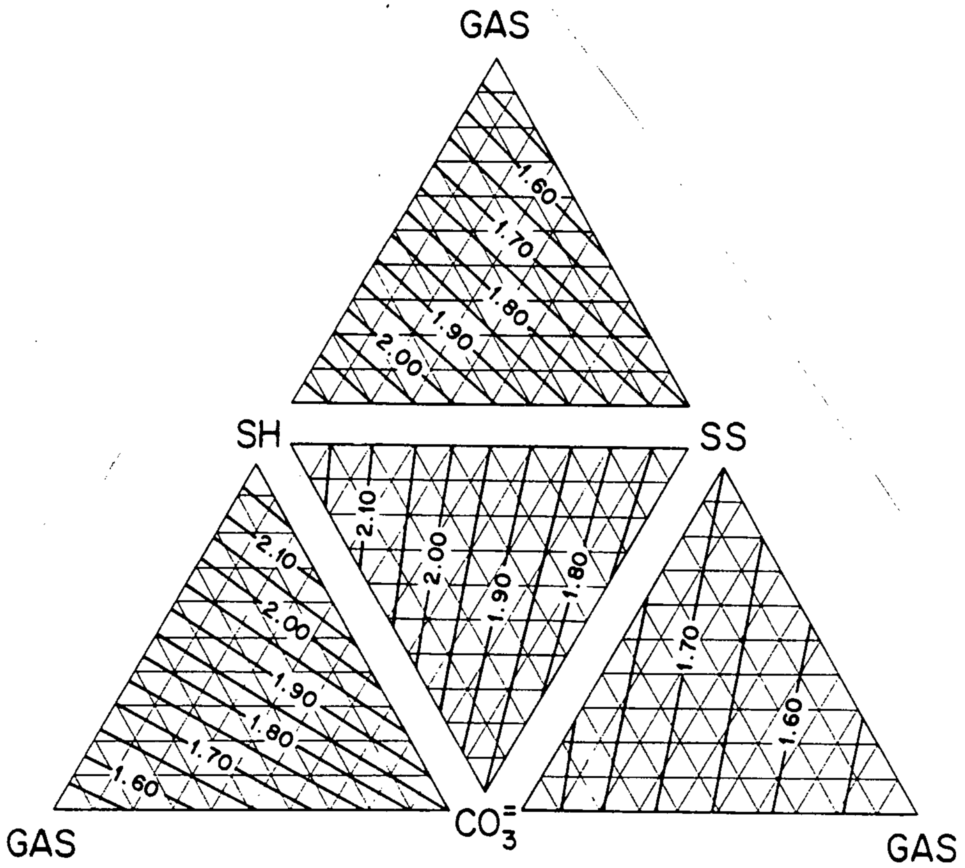


FIG. 4. Vp/Vs values as a function of four components: sand, shale, carbonates, and gas-saturation (Tatham, 1985)

SOURCE RECEIVER	X	Y	Z
X	SV		P/SV
Y		SH	
Z	SV/P		P

FIG. 5. Elastic-wave recording matrix showing different wave modes. Diagonal elements have received the most attention in the past. Isotropic converted waves are shown. Anisotropic modes fill the other off-diagonal elements (Garotta, 1985).

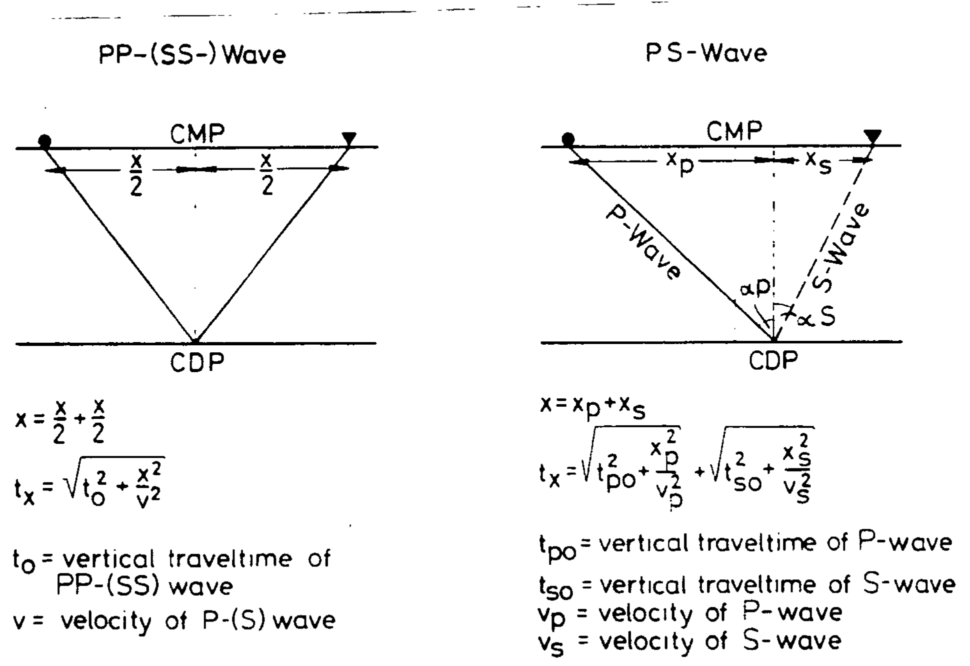


FIG. 6. Raypaths for pure P or S waves and converted (P-S) waves (Behle and Dohr, 1985).

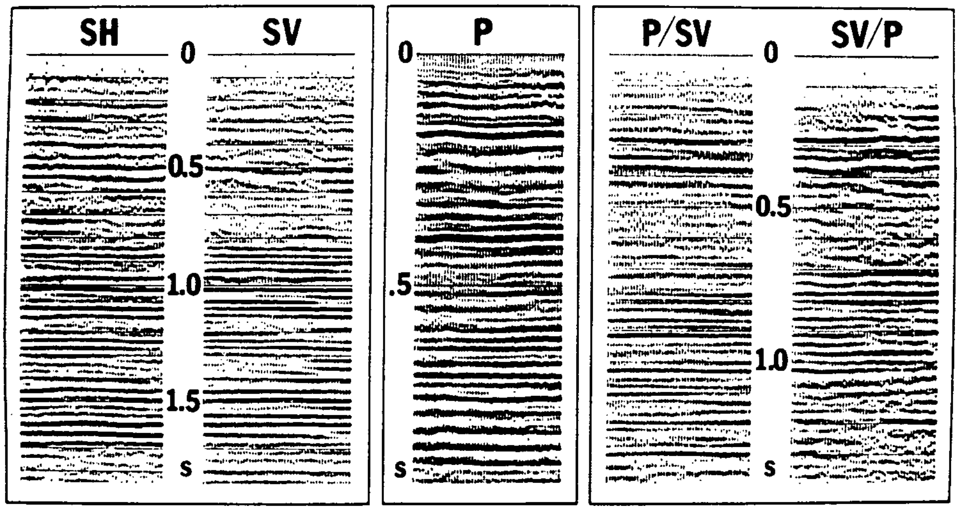


FIG. 7. Full isotropic elastic sections. The five isotropic wave modes are SH-SH, SV-SV, P-P, P-SV, and SV-P (after Garotta, 1985).

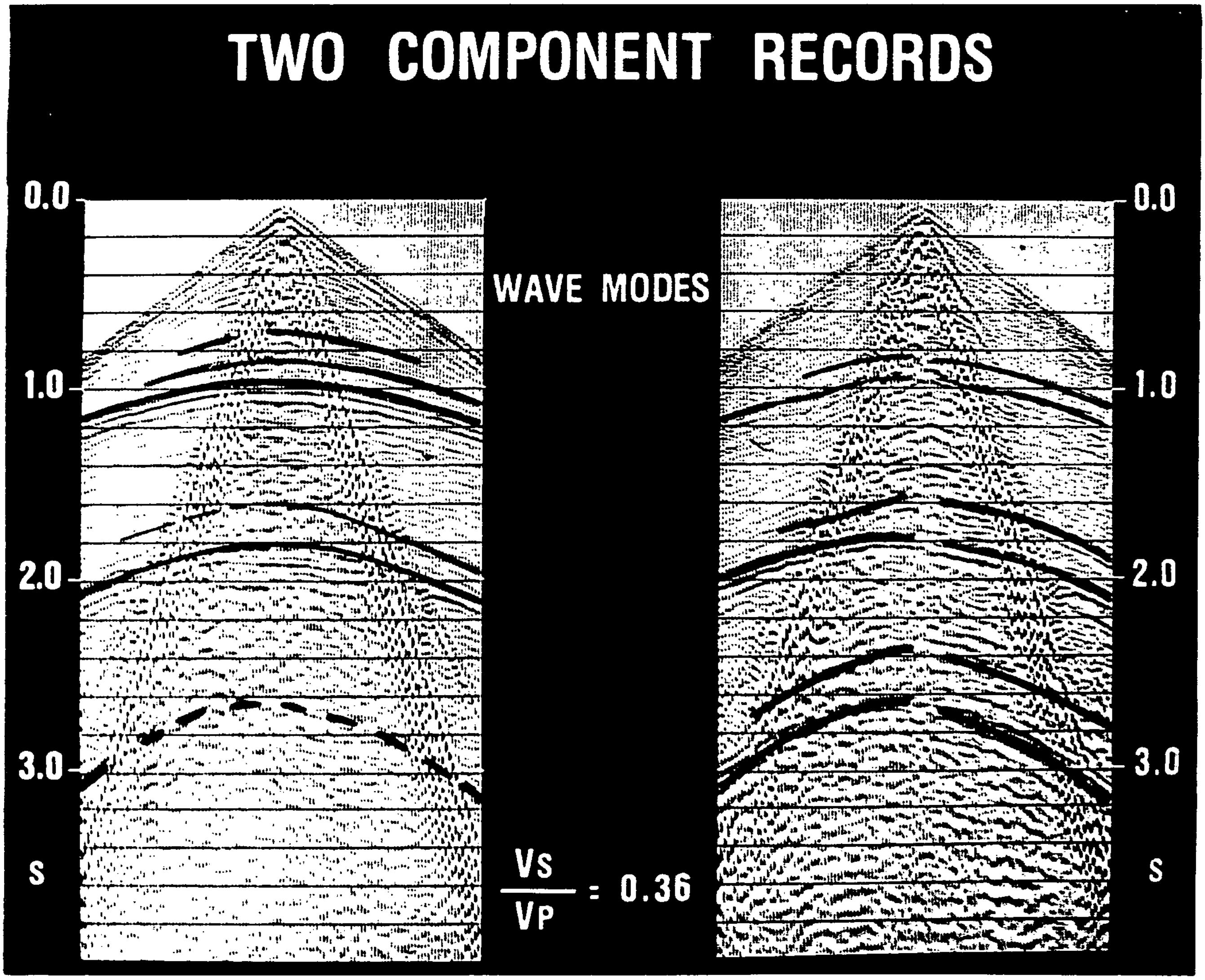
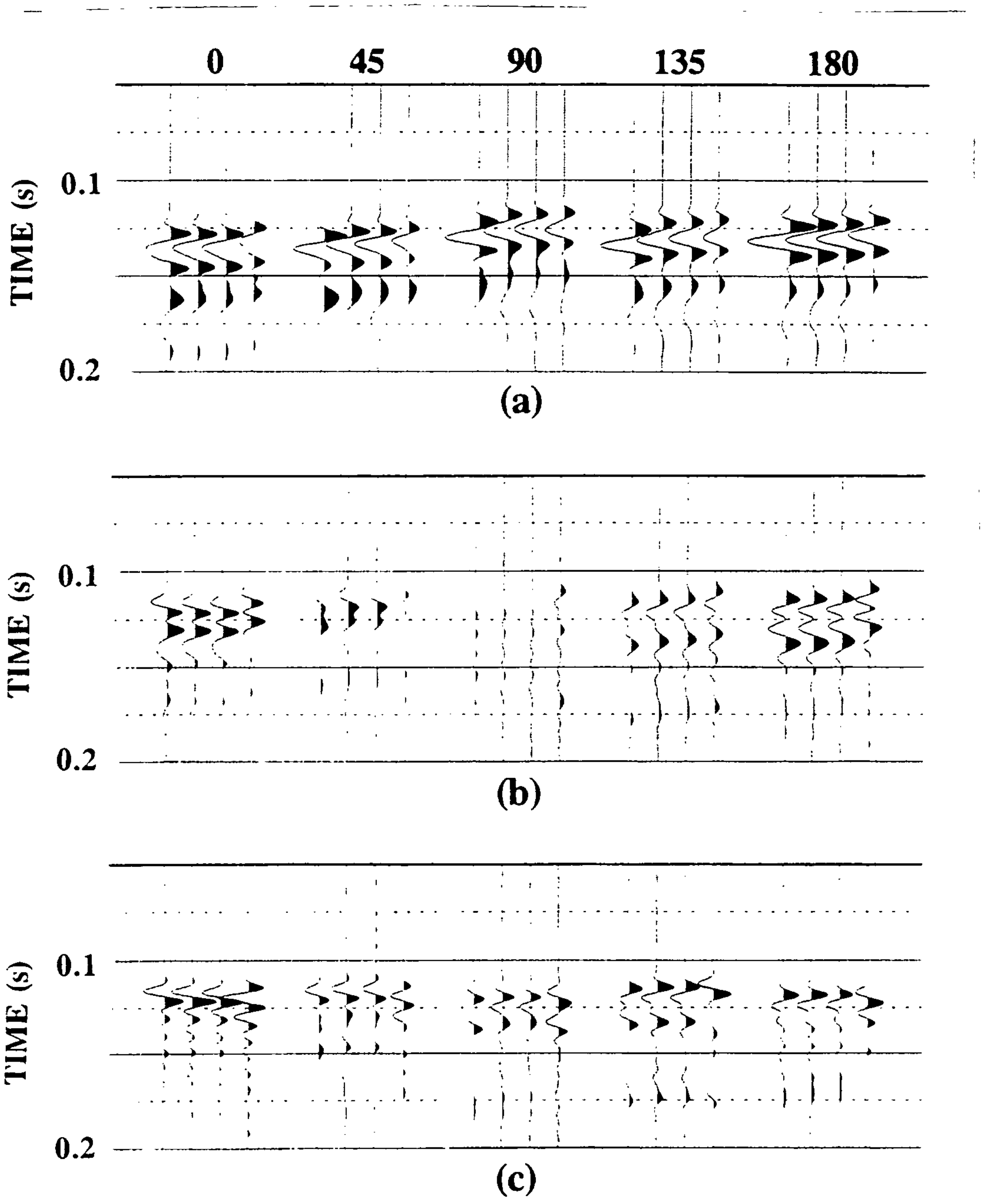


FIG. 8. Two-component (vertical and in-line) records (Garotta et al., 1985).



Common V/V (source/receiver) gathers for all shotpoints. The trace order in each panel (left to right) is: Geosource, Litton, Oyo Omniphone. **(b)** Common R/H1 gathers for all shotpoints. Trace order as in (a). **(c)** Common T/H2 gathers for all shotpoints. Trace order as in (a).

FIG. 9. 3-C geophone tests, showing high fidelity of all geophones except the Omniphone (Lawton and Bertram, 1993).

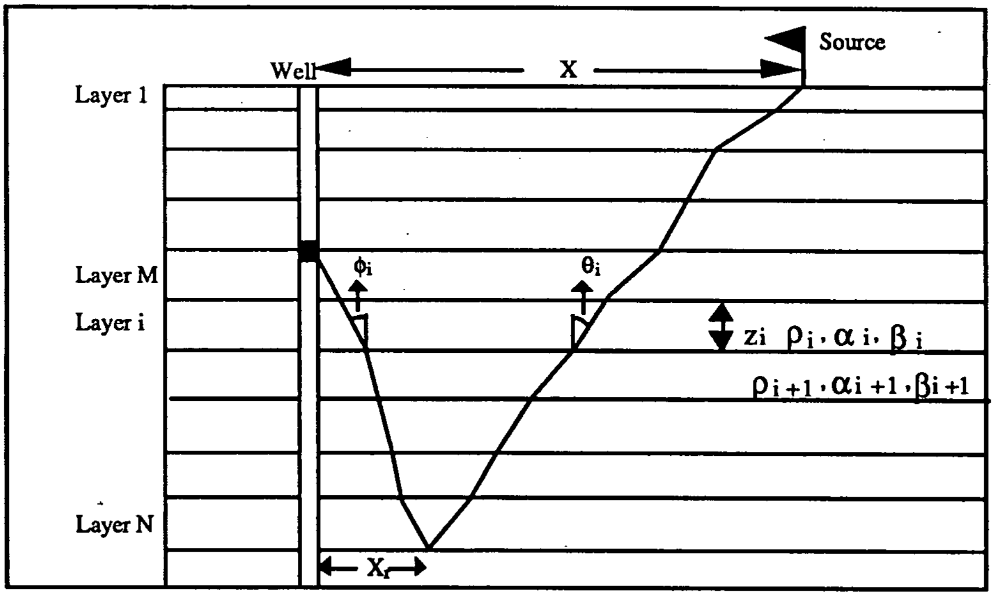


FIG. 10. Ray geometry for P-SV waves with source and receiver at differing elevations in a layered medium (Stewart, 1991).

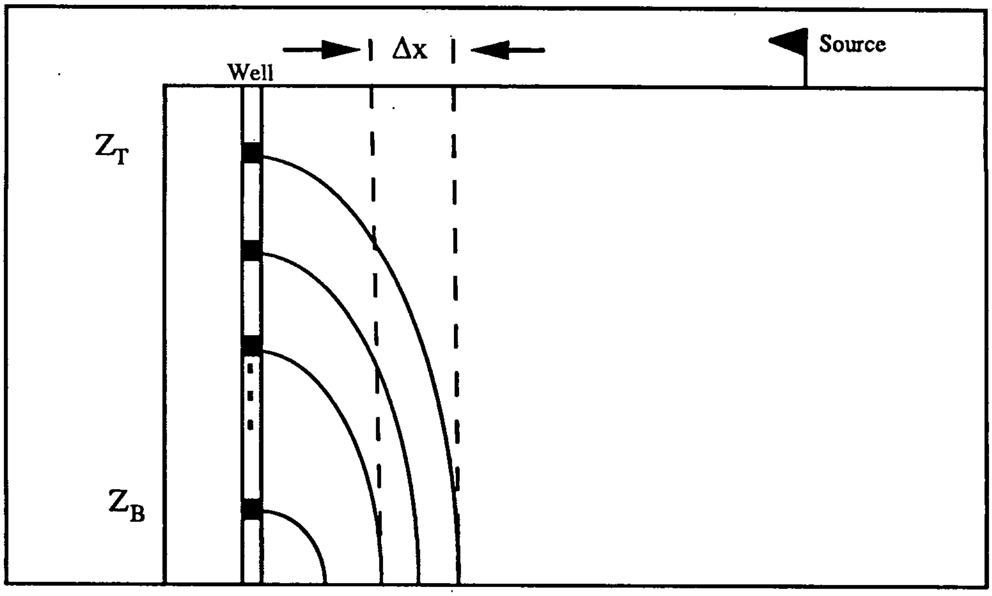


FIG. 11. Stacking corridor for P-SV reflections (Stewart, 1991).

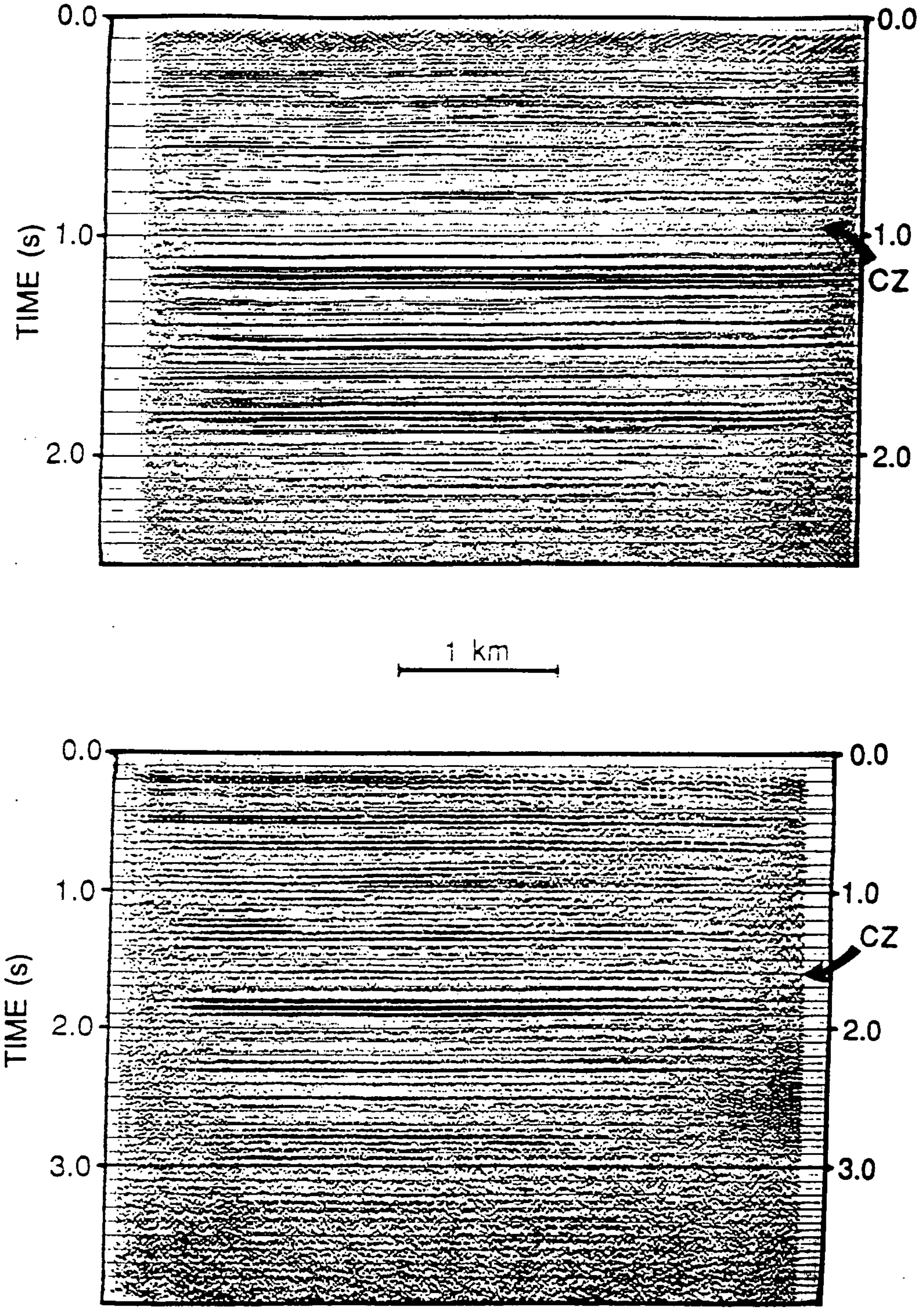


FIG. 12. P-P and P-SV sections from Carrot Creek, Alberta (Eaton et al., 1991).

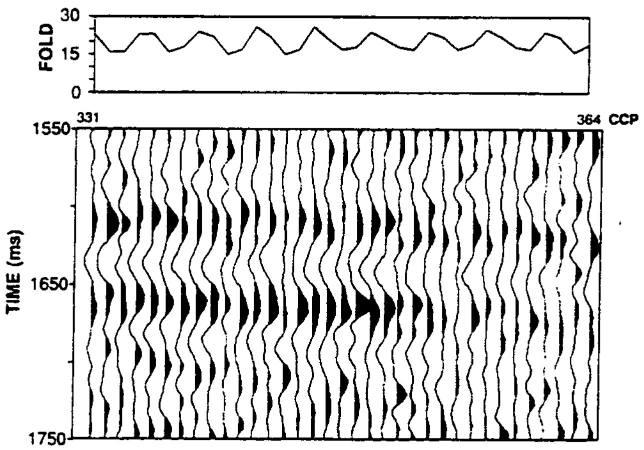


FIG. 13. Stack section periodicity correlated with stacking fold (Eaton and Lawton, 1992).

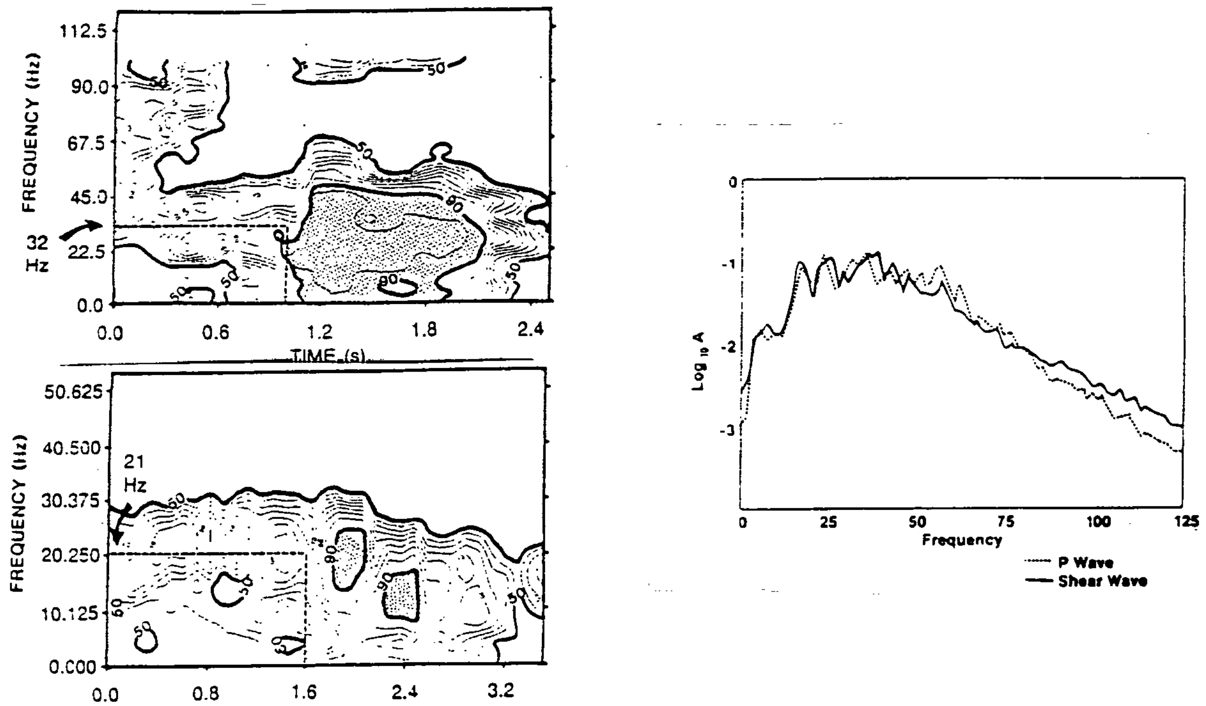


FIG. 14. Frequency content of P-P and P-SV stacked sections from Carrot Creek, Alberta (Eaton et al., 1991) and VSP data from Rolling Hills, Alberta (Geis et al., 1990).

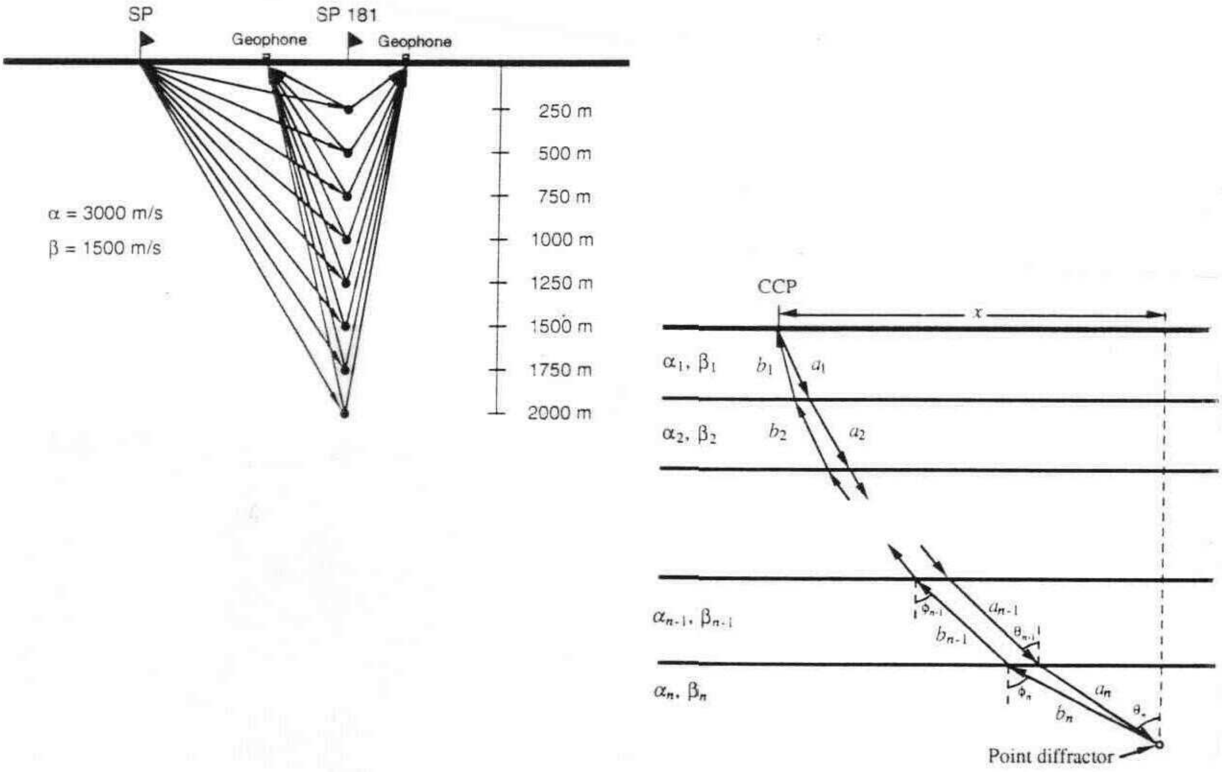


FIG. 15. Raypaths for diffracted P-SV energy from simple model (Harrison and Stewart, 1993).

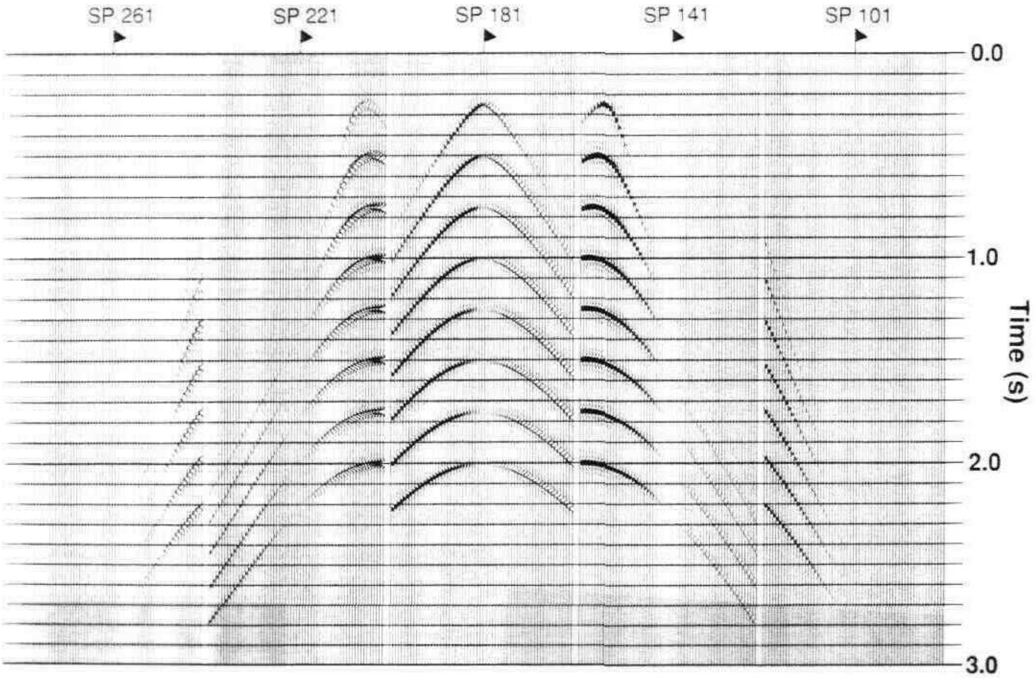


FIG. 16. Synthetic shot records for P-SV data from previous model (Harrison and Stewart, 1993).

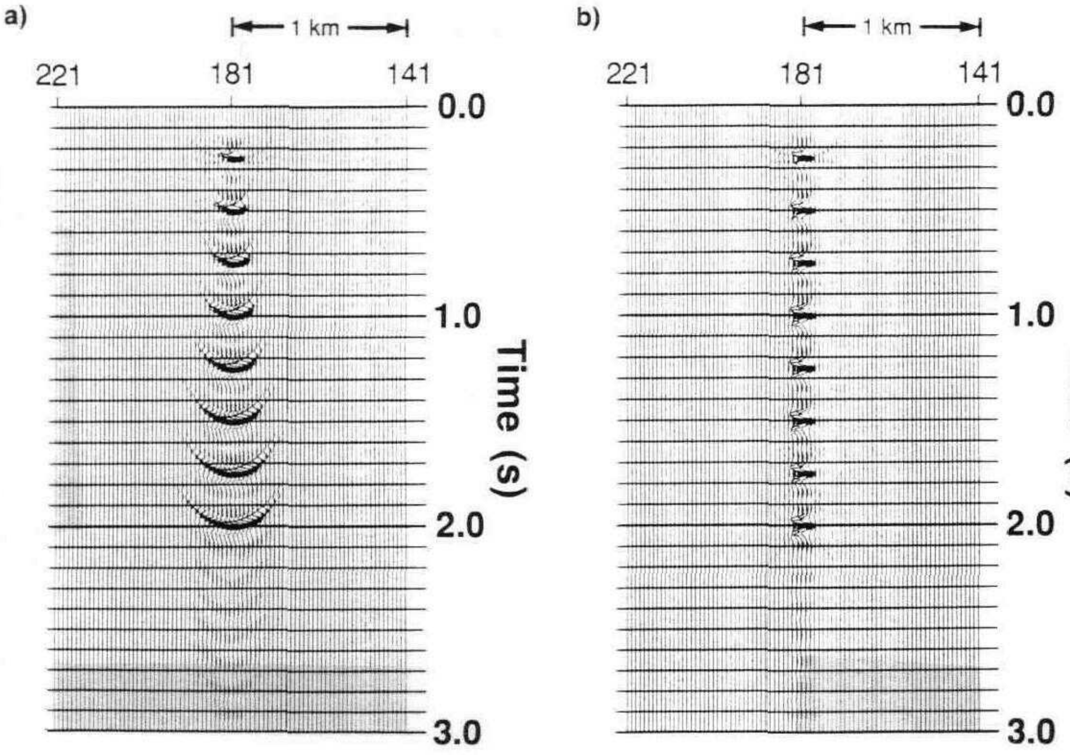


FIG. 17. DMO-stacked section after migration with the rms velocity and migration-velocity (Harrison and Stewart, 1993).

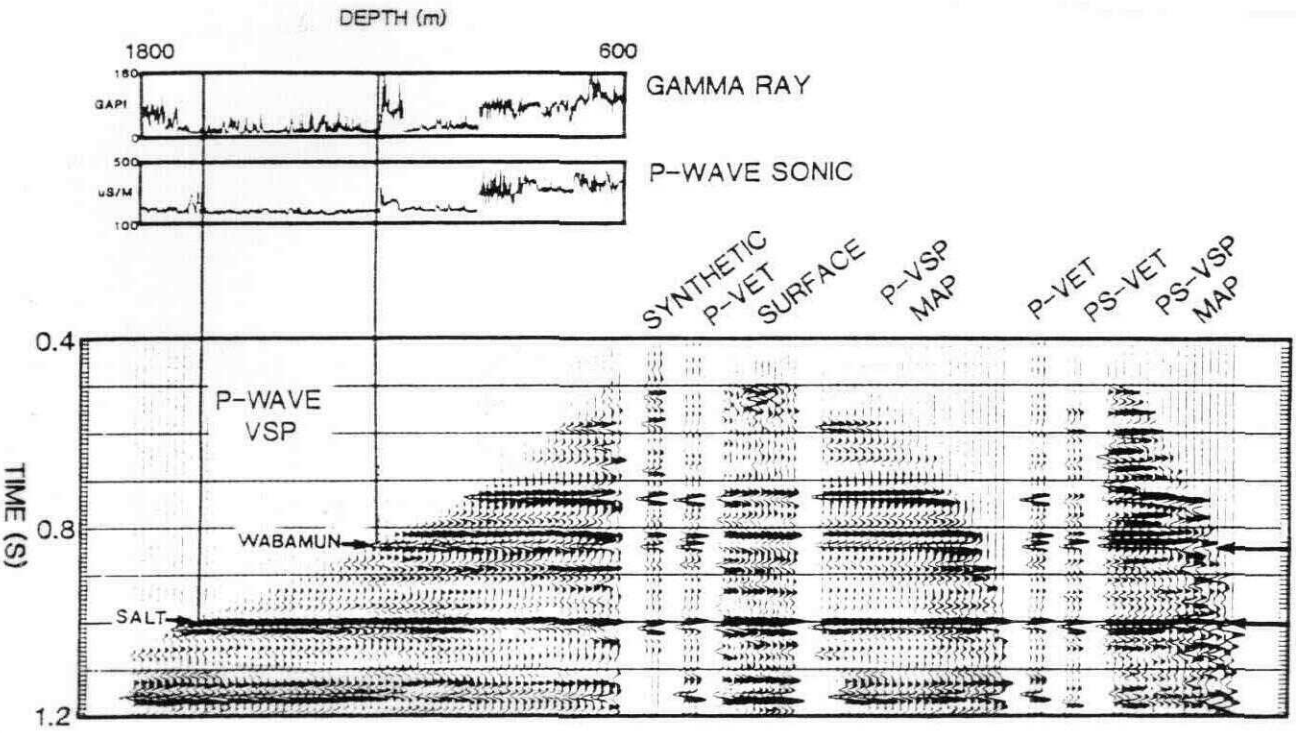


FIG. 18. L-plot display incorporating P-wave and P-SV data (Geis et al., 1990).

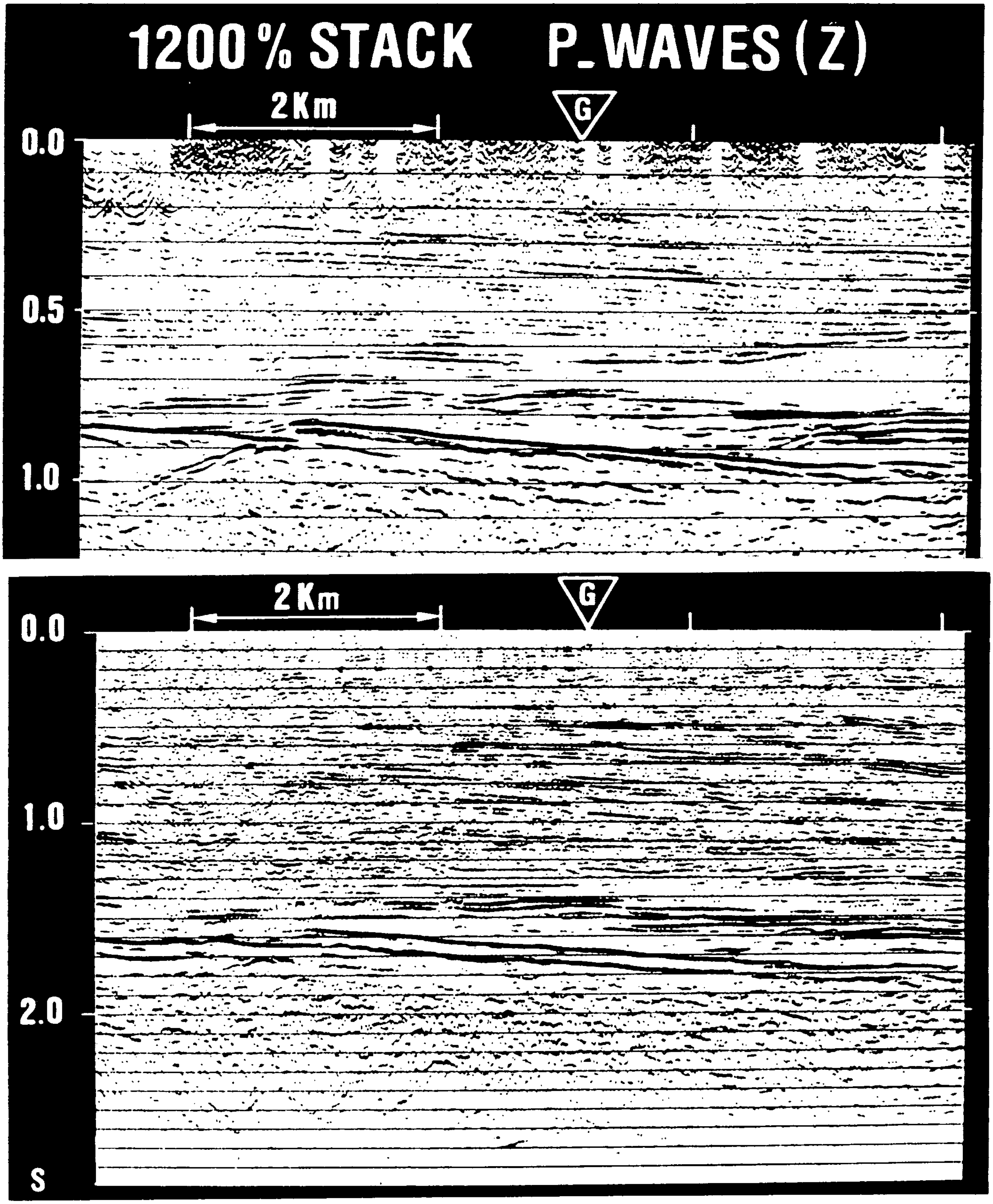


FIG. 19. P-P and P-SV sections from Viking sand example, Alberta (Garotta et al., 1985).

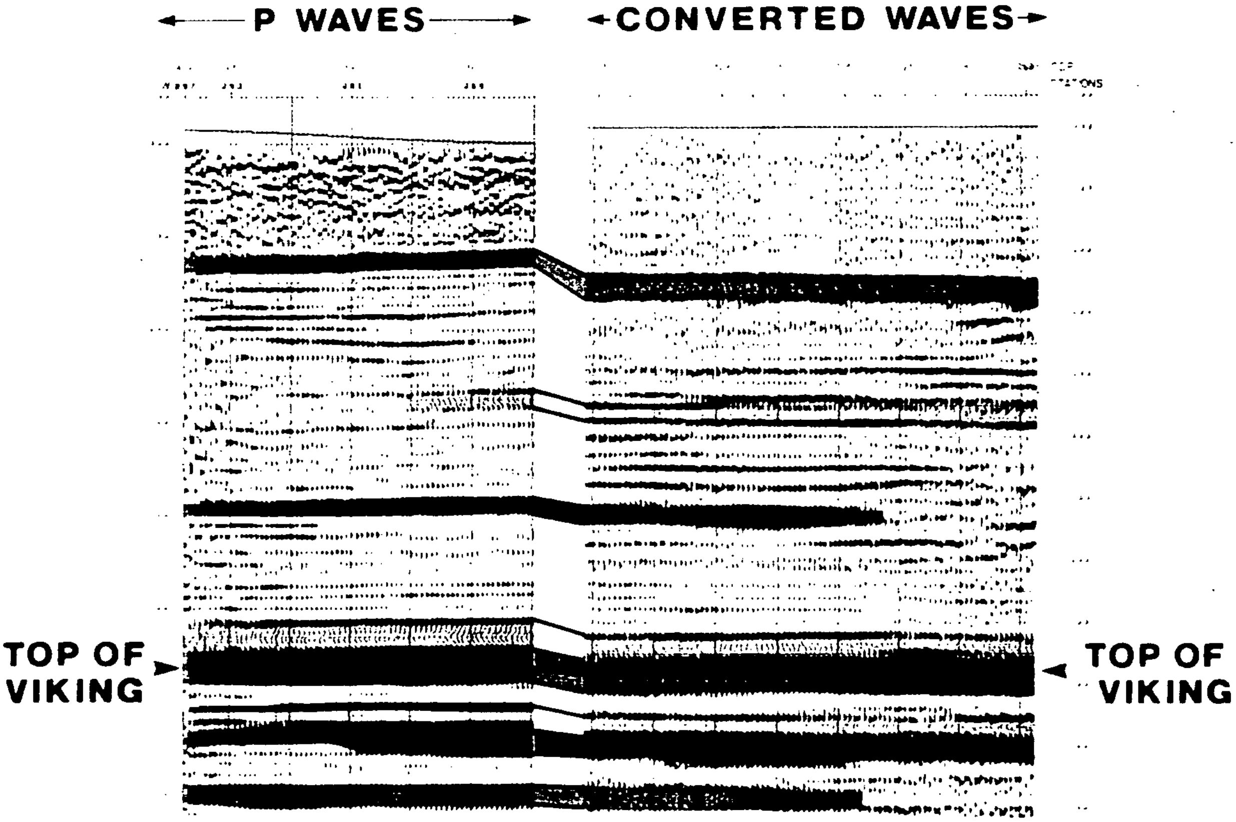


FIG. 20. P-P and P-SV sections with an interpreted correlation (Garotta et al., 1985).

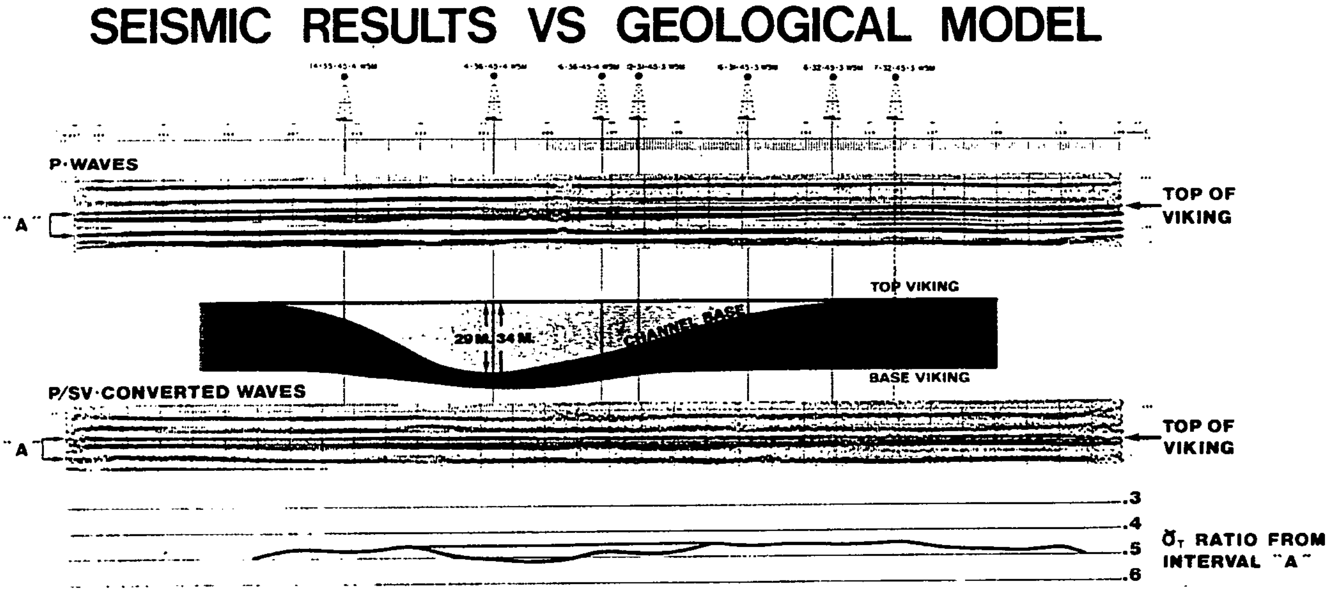


FIG. 21. Channel sand interpretation from the Vp/Vs ratio (Garotta et al., 1985).

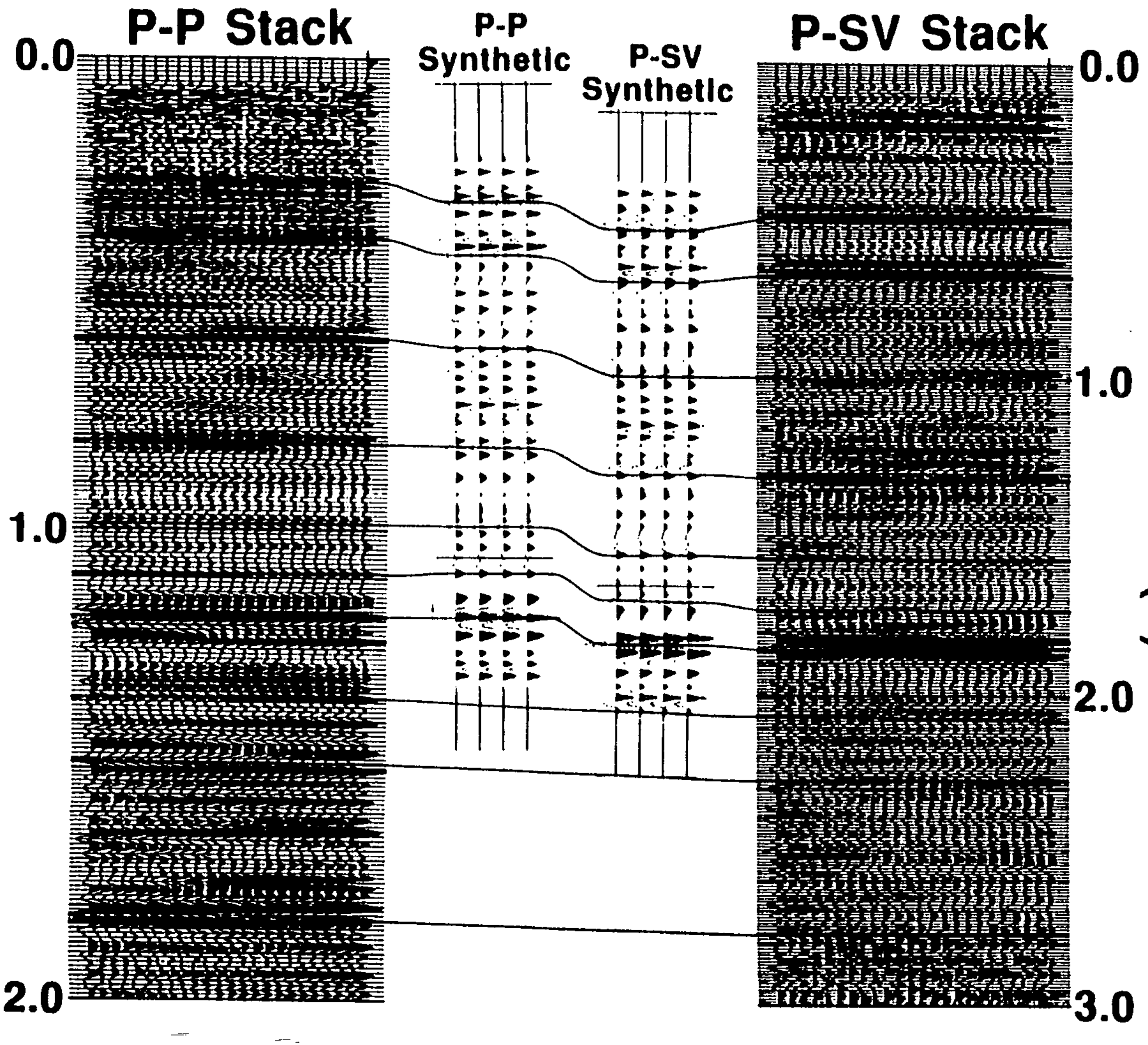
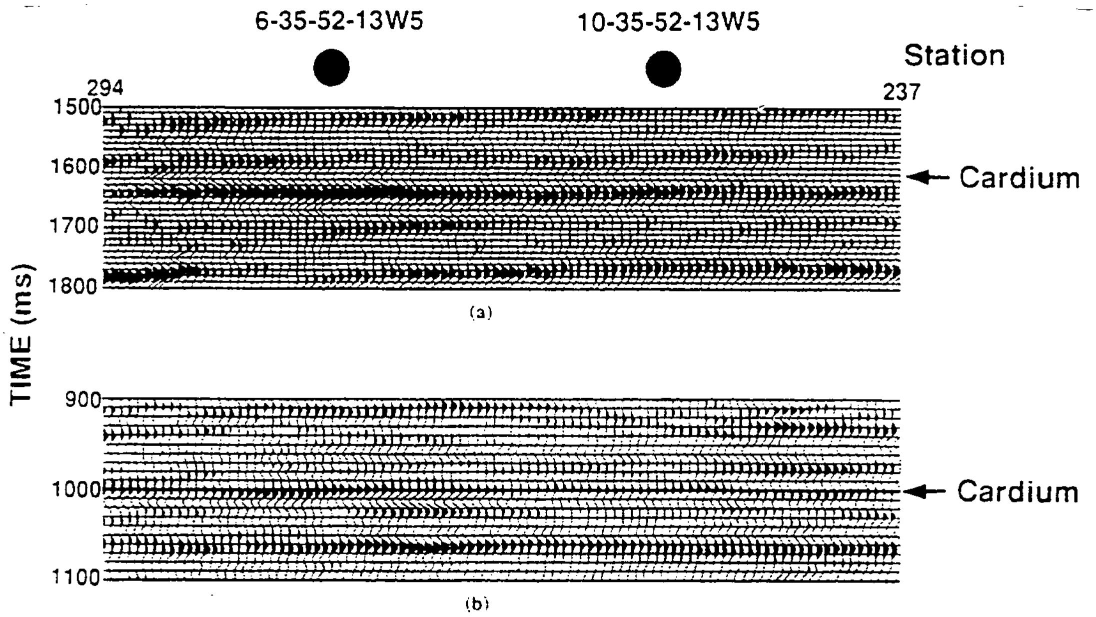


FIG. 22. P-P and P-SV stacked sections from Carrot Creek, Alberta with synthetic seismograms and correlations (Nazar and Lawton, 1993).



Geologic Marker	Depth (m)	Thickness (m)	V_P (m/s)	V_S (m/s)	V_P/V_S	σ	Density (kg/m^3)
Surface	0	355	2800	1033	2.68	0.42	2370
Edmonton	355	200	3226	1453	2.22	0.37	2370
Marker A	555	470	3200	1517	2.11	0.36	2370
Belly River	1025	290	4150	2268	1.83	0.29	2450
Lea Park	1315	117	3650	1780	2.05	0.34	2500
Colorado	1432	178	3920	2031	1.93	0.31	2380
Cardium (congl.)	1605-1620	5-20	4327	2591-2704	1.60-1.67	0.18-0.22	2610
Blackstone	1625	80	4003	2074	1.93	0.31	2510
Base of Blackst.	1690	85	3900	2308	1.80	0.25	2550
Second White Specks	1775	150	3600	2081	1.73	0.25	2450
Viking	1925	33	4400	1543	1.73	0.25	2600
Joli Fou	1958	14	3800	2197	1.73	0.25	2300
Mannville	1972	-	4200	2428	1.73	0.25	2600

FIG. 23. Cardium event in P-SV sections and P-P sections and rock properties (Nazar and Lawton, 1993).

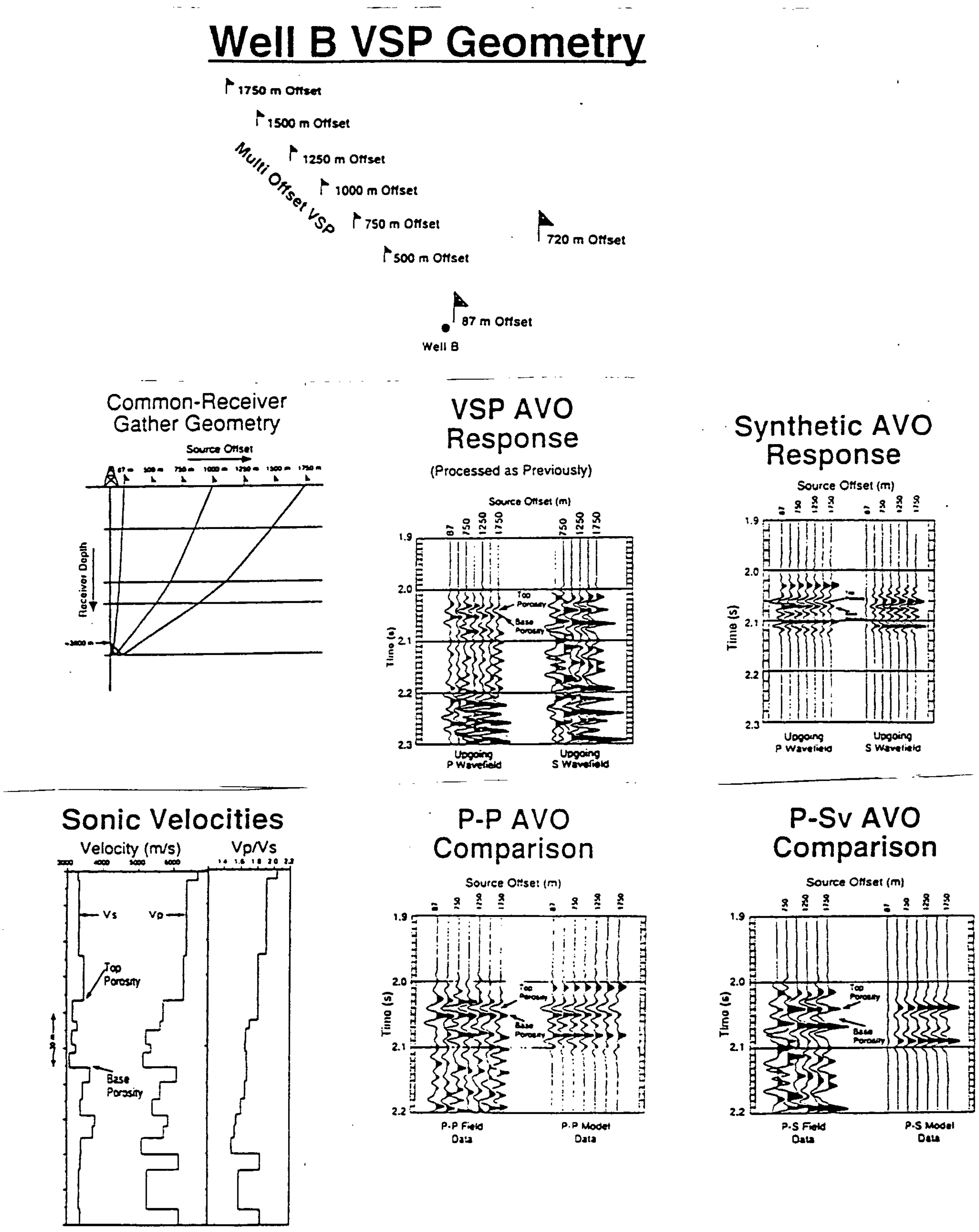


FIG. 24. AVO effects in the VSP data for P-P and P-SV waves (Coulombe at al., 1992).

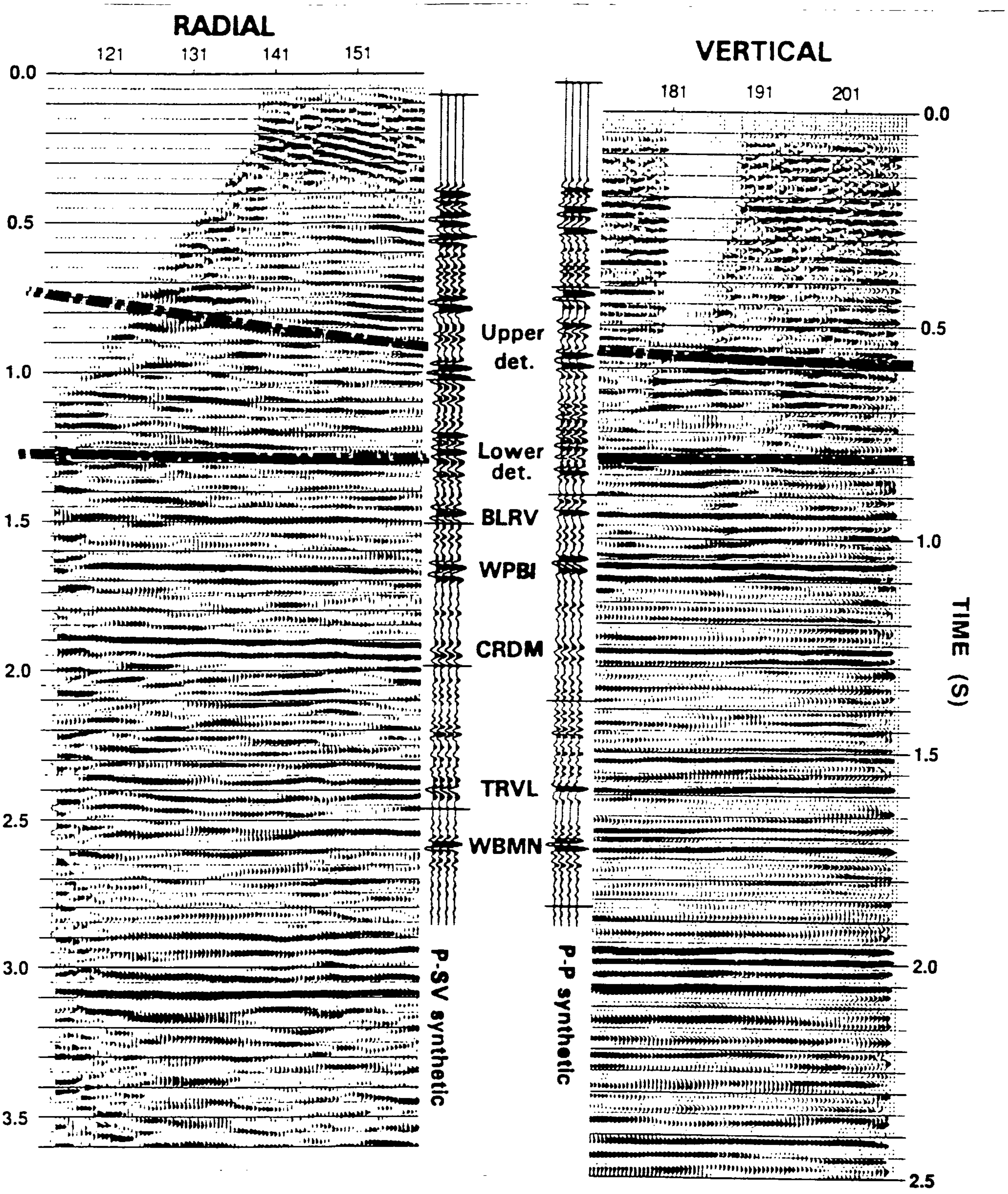


FIG. 25. P-SV and P-P sections and correlation for data from Springbank, Alberta (Lawton and Harrison, 1993).

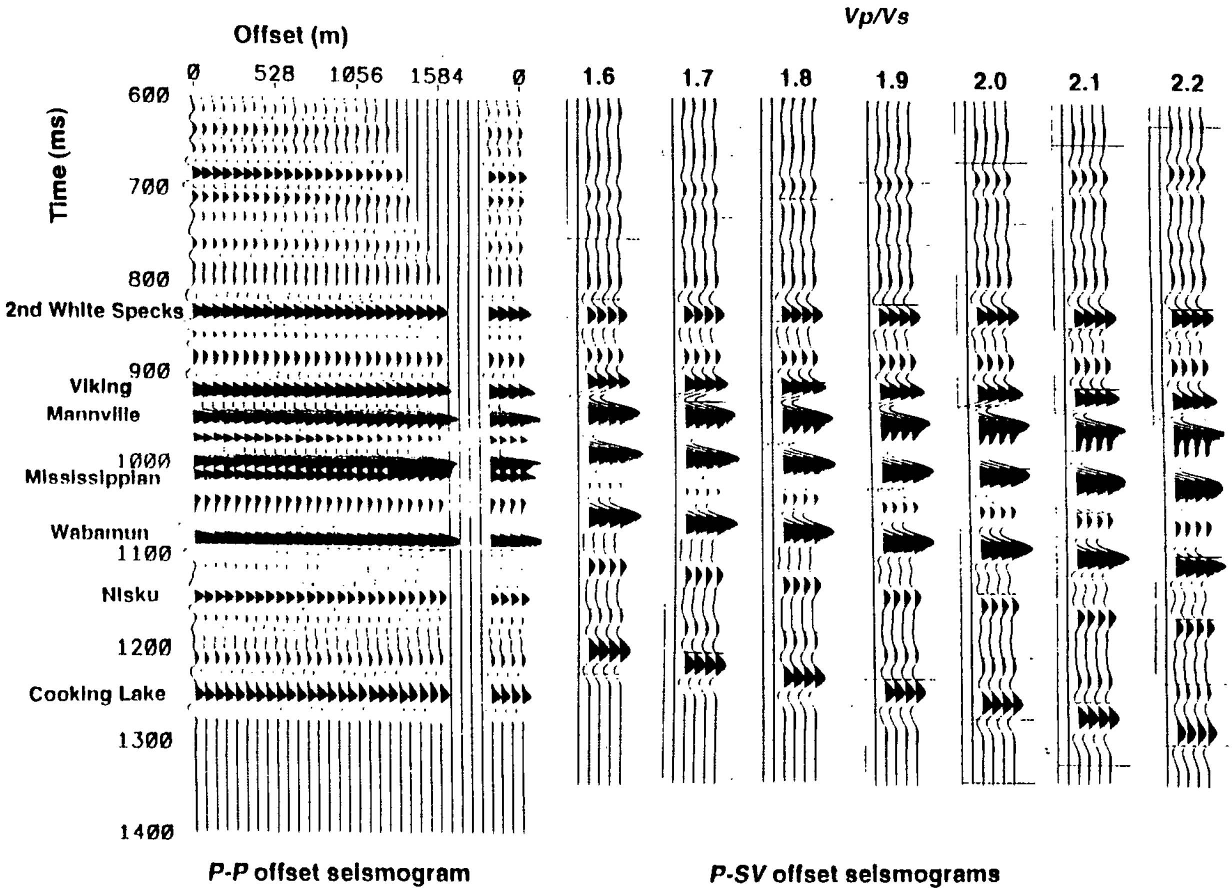


FIG. 26. Offset synthetic seismograms from the Lousana, Alberta area (Miller et al., 1994) showing the effect of a varying Vp/Vs value.

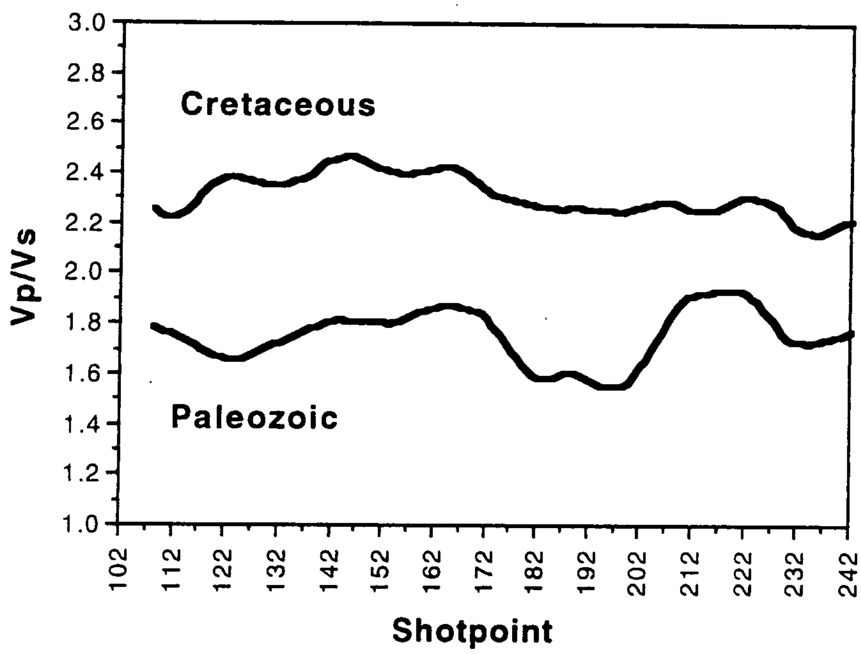


FIG. 27. Vp/Vs value extracted from the interpreted P-P and P-SV sections. The Vp/Vs values in the Cretaceous are indicative of a clastic section while those in the Paleozoic are characteristic of carbonate rocks. The lower values in the Paleozoic, from shot point 172 to 212, are coincident with an underlying oil-bearing reef. The reef may have had some effect on the subsequent deposition leading to a seismically visible anomaly (Miller et al., 1994).

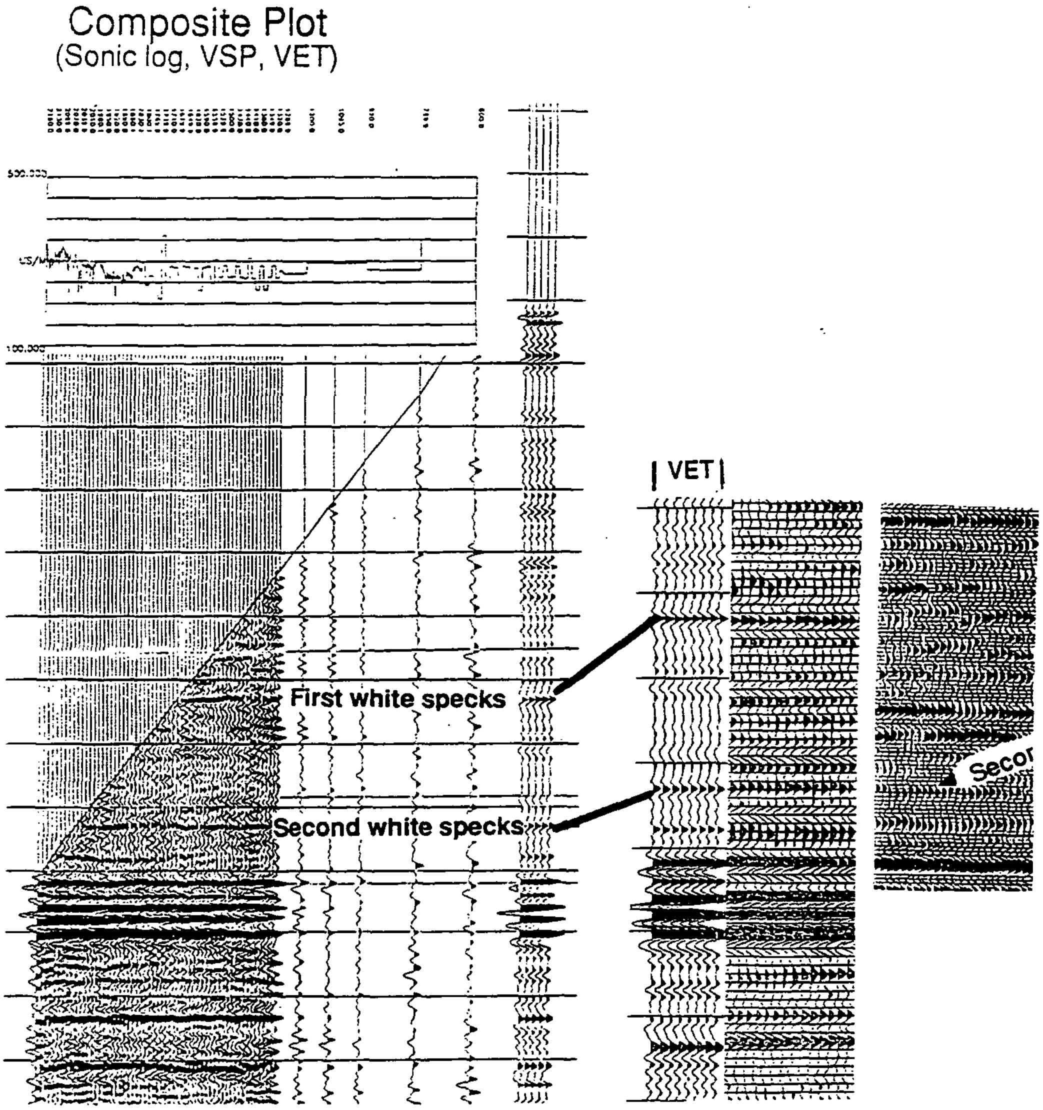


FIG. 28. Interpretation of log, VSP, and surface seismic data from the Willesden Green, Alberta region.

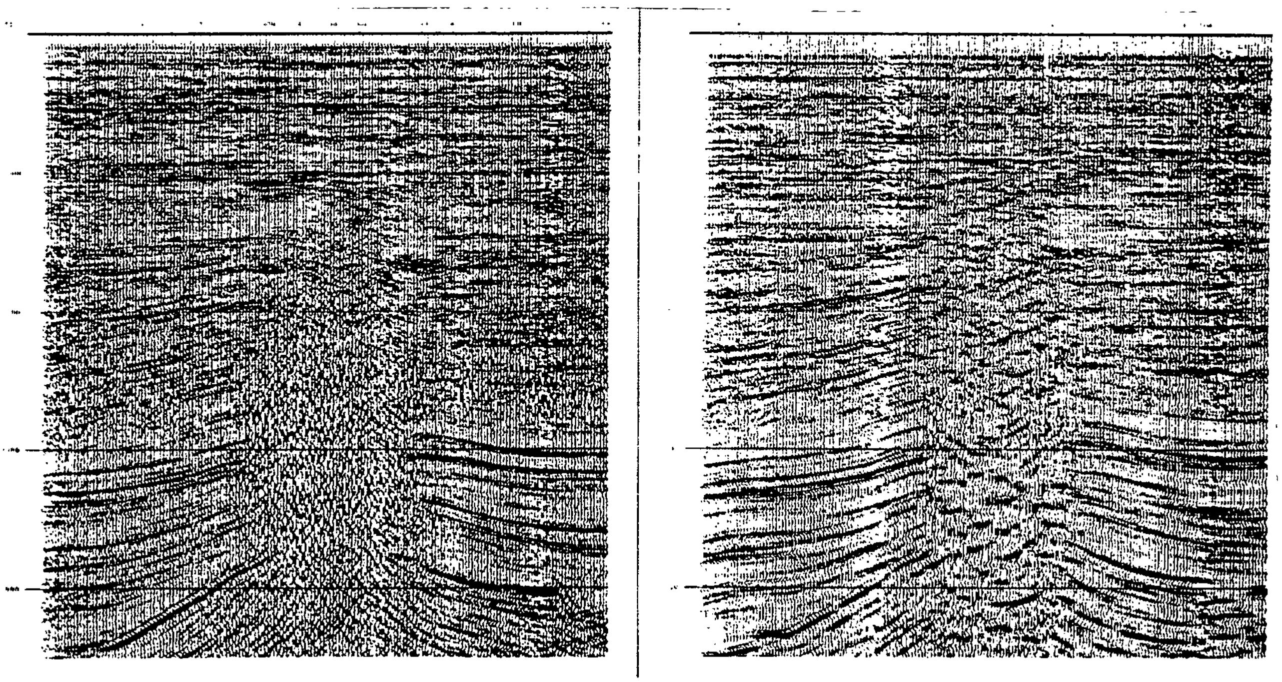


FIG. 29. Conventional P-wave section and SUMIC (sub-sea seismic)P-wave sections (Berg et al., 1994).

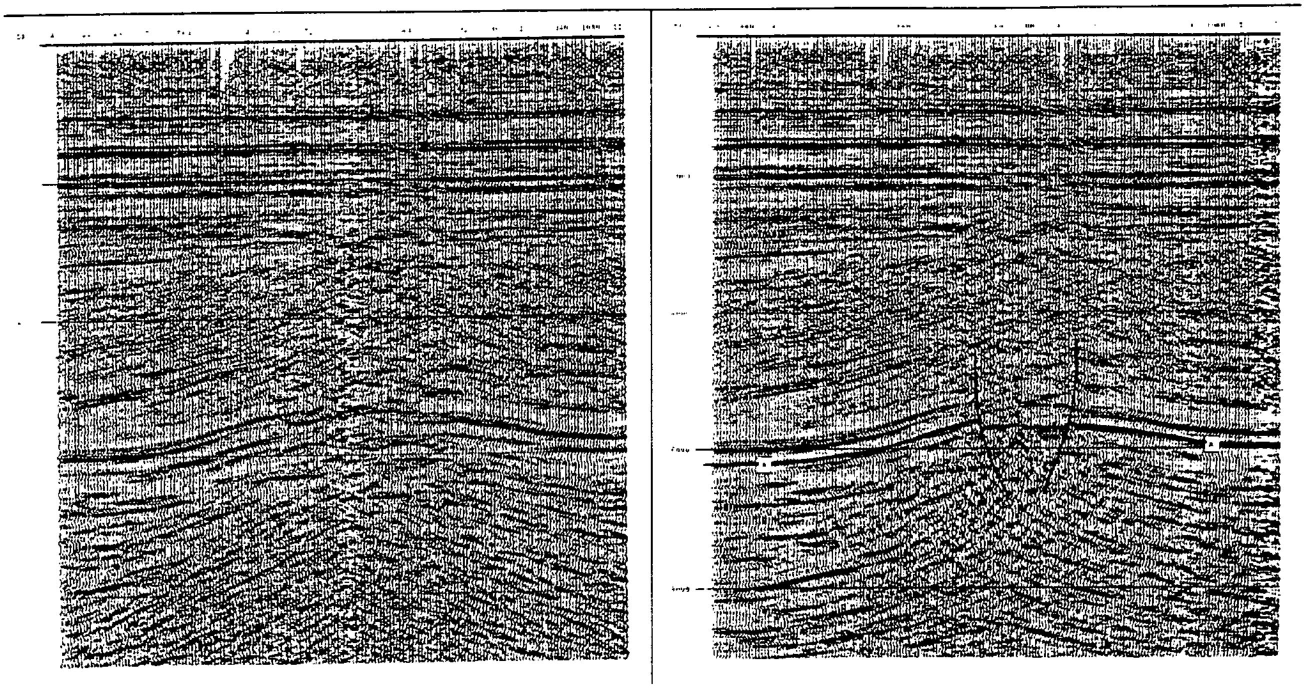


FIG. 30. SUMIC S-wave sections with and without interpretation (Berg et al., 1994)

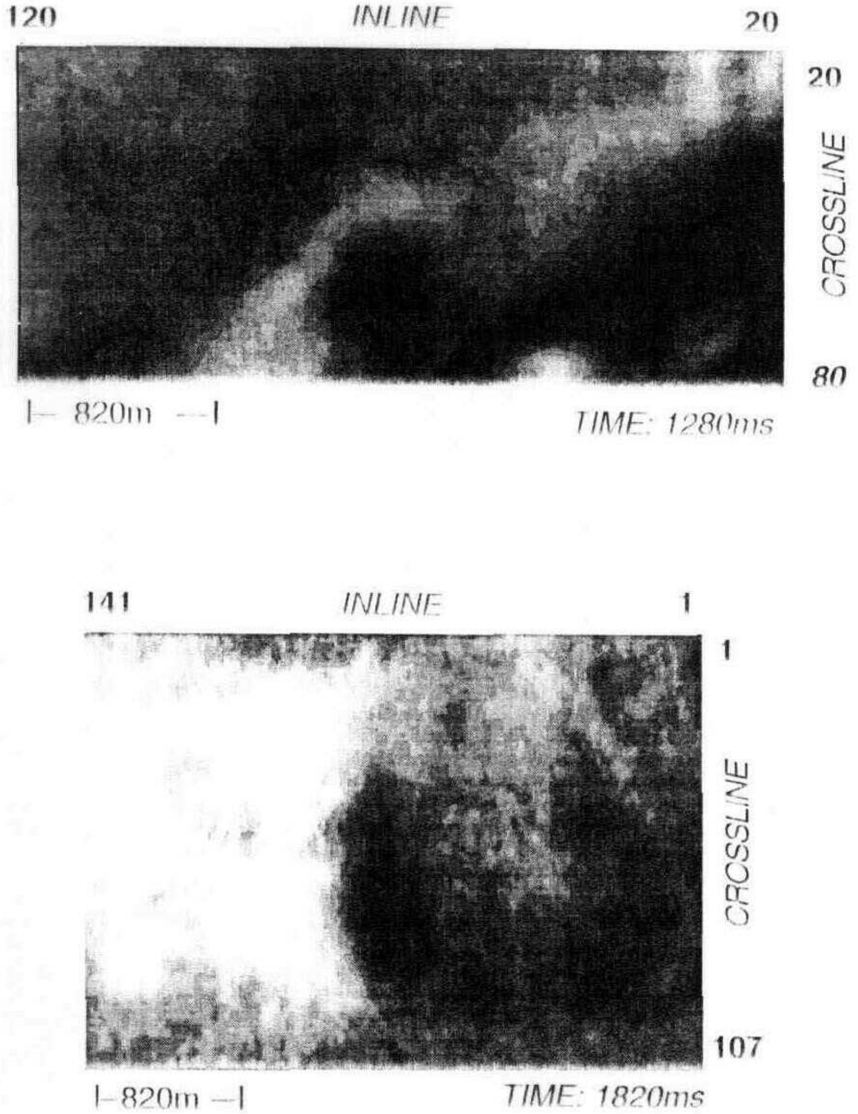


FIG. 31. 3-D time slices of P-P and P-SV seismic data. The Leduc pinnacle reef is located at the centre of both slices (Larson and Stewart, 1994).