# Improvement of P-data using 3-C seismic data

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## ABSTRACT

The separation of the individual P and S arrivals may be considered a problem since the P and SV data are recorded in both vertical and horizontal (in-line) geophones. Due to the intrinsic geophone characteristics, P and S waves are observed on both geophones. A method of separating P and S waves in the $\tau$-p domain is presented which inverts both vertical and horizontal geophone records for the receiving characteristics, thereby separating the two wavetypes.

The filter coefficients are determined from the near-surface P and S wave velocity and from the geometry of the geophone groups. The P/S separation was tested using synthetic and real data. In both cases, the method is demostrated capable of separating PS and SP converted reflections and appears to be stable and have low sensitivity to errors in the near-surface P and S wave velocity and to noise in the data.

## INTRODUCTION

2D surface seismic data had proved to be a helpful tool for obtaining important information on subsurface parameters such as lithology, porosity, porefill, etc. This data usually is acquired using a single-component, vertical geophone which works very well for what it was designed to do: record the particle motion associated with nearly vertically traveling P-waves. This assumption works well as long as the subsurface is fairly flat, the near surface has low-velocities, and there is nor shallow structures. But structural deformations occur in many sorts of basins. Seismic waves that have been scattered from high-angle features will not necessarily arrive at the surface along nearly vertical rays and converted modes occur interfering with PP data doing the records difficult to analyse.

In the seismograms obtained from 3-C geophones it is possible to see different types of events: refractions, surface waves, and shear waves, along with primary P waves. These waves are recorded in their "true amplitude" motion (Ameely et al., 1985).

Usually it is considered that all the information related to P-waves is contained in the vertical channel but due to the geophone receiving characteristics, P and SV are observed on both horizontal and vertical geophones then the recognition and separation of the individual P and SV arrivals may form a considerable problem. "The disturbing events" present in both channels are in most cases so intermingled that they cannot be separated visually and therefore are often regarded as "noise". The "noise" could be converted into signals if we found a way to discriminate individual "noise" components and describe them by laws of wave propagation. Perhaps, the separation process acquire a strong importance, due to this can give us a real P and SV waves registers and however improve our description and definition of the subsurface.

Many papers have shown that the shear waves complement the information given by the P waves due to its different behavior in the presence of fluid saturation and fractures related to reservoirs (Helbig and Mesdag, 1982; Meissner and Hegazy, 1981). As results, it is essential a method which permit us to separate both P and S waves recovering its remanent energies on the vertical and horizontal records.

## OBJECTIVE

The objective of this work is to develop an algorithm that uses 3-C data in a 2-D data set to improve the imaging of structure and lithology of the subsurface.

This work is an extention of the main ideas proposed by Dankbaar about the development of a new P/S separation filter. Dankbaar proposed the separation of the P and SV waves from 3C-2D data through removing of the effects of the geophone receiving characteristics in the f-k domain (Dankbaar, 1985). In the present study is developed the P/S separation filter in the $\tau$-p domain and the obtained results compared with which achieved by Dankbaar. Both domains f-k and $\tau$-p let us isolate P and S waves as well as remove noise (ground roll, multiple reflections, etc) using specific properties of these waves after the transformation. In particular, the $\tau$–p domain exploits the behavior of the apparent slowness p associated with each wave.

## THEORY

The P/S separation method is based on the receiving geophone characteristics. The receiving characteristic describes the amplitude at a receiver due to an incident wave as a function of its angle of incidence.

In the P/SV-case considered here, only four types of geophone characteristics are involved, distinct for vertical and horizontal geophones and for incident P and S waves. The radiation characteristics for single vertical and horizontal surface-forces, equivalent to the receiving characteristics of vertical and horizontal geophones are shown in the Fig. 1 (Miller and Pursey, 1954). Its dependence on $V_p$ and $V_s$ velocities is indicated in the same figure for a range of values of both parameters. It is evident from this figure that both incidnet P and incident S waves are observed on vertical and horizontal geophone records due to the overlapping of the radiation characteristics associated with both waves for certain angles of incidence (30°- 60°).

As Dankbaar pointed out the expressions for the characteristics of single geophones can be written as a function of horizontal slowness p

$$R_v^p(p) = 2\theta^{-1}\xi\left(2V_s^2p^2 - 1\right)/R_0(p) \tag{1}$$

$$R_v^s(p) = 4V_s p\xi\eta/R_0(p) \tag{2}$$

$$R_h^p(p) = 4V_p p\xi\eta/R_0(p) \tag{3}$$

$$R_h^s(p) = 2\eta\left(1 - 2V_s^2p^2\right)/R_0(p) \tag{4}$$

where

$$\theta = V_s/V_p,\ \xi = \left(\theta^2 - V_s^2p^2\right)^{1/2},\ \eta = \left(1 - V_s^2p^2\right)^{1/2}, \text{and } R_0(p) = \left(1 - 2V_s^2p^2\right)^2 + 4p^2V_s^2\xi\eta.$$

The effect of the receiving characteristics on an incident SV wave, radiated by a point source and reflected at a horizontal interface, as functions of angle of incidence (0° - 50°) is shown in the Fig. 2. Due to the receiving characteristics of the vertical and horizontal geophones the S wave displacement is recorded with different behavior on both records showing changes in amplitude and phase (Fig. 2d,e).

An useful way to express the P/S separation filter represents the horizontal and vertical geophone records in terms of receiving characteristics and P and S waves. Since, in general, the receiving characteristics are a function of frequency and horizontal wavenumber, it is advantageous to decompose the data into plane waves, i.e. to transform the data to the $\tau$-p domain. Then the expressions take quite simple forms as

$$U_v(\tau,p) = P_{in}(\tau,p)R_v^p(\tau,p) + S_{in}(\tau,p)R_v^s(\tau,p) \tag{5}$$

$$U_h(\tau,p) = P_{in}(\tau,p)R_h^p(\tau,p) + S_{in}(\tau,p)R_h^s(\tau,p) \tag{6}$$

where $U_v$ and $U_h$ are the vertical and horizontal geophone records transformed on the tau-p domain and $P_{in}$ and $S_{in}$ the incident P and S wavefields, respectively.

Given the near-surface P and S wave velocity, the receiving characteristics $R_v^p$, $R_v^s$, $R_h^p$, and $R_h^s$ are determined resulting in two equations with two unknowns, which represent the incident P and S waves. The solution of these equations is straightforward

$$P_{in}(\tau,p) = F_v^p(\tau,p)U_v(\tau,p) + F_h^p(\tau,p)U_h(\tau,p) \tag{7}$$

$$S_{in}(\tau,p) = F_v^s(\tau,p)U_v(\tau,p) + F_h^s(\tau,p)U_h(\tau,p) \tag{8}$$

The coefficients $F_v^p$, $F_v^s$, $F_h^p$ , and $F_h^s$ are functions of receiving characteristics R and can be considered as filter coefficients. Their expressions considering single geophones will be given by

$$F_v^p(p) = -\left(1 - 2V_s^2p^2\right)/2\left(1 - V_p^2p^2\right)^{1/2} \tag{9}$$

$$F_h^s(p) = V_s^2p/V_p \tag{10}$$

$$F_v^s(p) = V_sp \tag{11}$$

$$F_h^s(p) = \left(1 - 2V_s^2 p^2\right) / 2\left(1 - V_s^2 p^2\right)^{1/2} \qquad (12)$$

The above equations were derived for a single geophones whose receiving characteristics are considered independent of frequency and completely determined by the near-surface P and S wave velocity $V_p$ and $V_s$. In the real case, where geophone groups are used, their receiving characteristics can be obtained from those for single geophones by multiplication with a group-effect factor, it can be shown that the filter coefficients for geophone groups are those for single geophones, divided by the group effect factor. This group effect factor G(D,N,k) was pointed out by Dankbaar as a function of frequency f and horizontal wavenumber k

$$G(D,N,k) = 2\sum_{j=1}^{N} \cos\left[kD(2j-1)\right] \qquad (13)$$

for an in-line group of 2N geophones coupled in phase with a distance 2D between individual elements. In this way the group effect is removed from the data before vertical and horizontal records are combine by the filter operation. If equal patterns are used for both geophones the data can be filtered without previous group effect correction, that means directly with the expressions shown in eqs. (9) - (12).

In other words, the coefficients indicated in the eqs. (9) - (12), as derived for single geophones, also perform a P/S separation on data recorded with geophone groups, provided the same group patterns for horizontal and vertical geophones are used. The correction for the geophone group effect may be applied after filtering for P/S separation. This shows that the filter coefficients perform a robust filter operation.

The Fig. 3 shows the basic steps followed by the P/S separation filter in the $\tau$-p domain. The procedure followed for calculating the direct and inverse $\tau$-p transformation is the same described by Stoffa, Buhl, Diebold and Wenzel (1981). Here the pass-P mode output consists of all waves that arrived at the surface e as P wave, with the correct amplitude and phase of the incident waves; all S wave energy is removed. The same principle is applied over the pass-S mode, which consist of all waves that arrived at the surface as S wave, with the correct amplitude and phase of the incident waves; all P wave energy is removed.

## APPLICATION AND RESULTS

For testing the program a horizontally-layered earth model was used as shown in Fig. 4. This model consist on five homogeneous layers on top of a half-space medium. The maximum reflector depth in this model is located at 200 m. We consider a geometry with one shot located at 0.0 m and 28 geophones spaced every 5 m, with an offset range of 5-140 m. This model was proposed by Dankbaar (1985) and used in this study for comparison between the results of P/S separation obtained with $\tau$-p and f-k methods. The synthetic data was calculated by a ray-tracing using the Uniseis seismic modelling package of Landmark which includes amplitude decay due to spherical divergence. Since we are concerned here with separation of P and S waves on geophone records, we assumed that in all directions the amplitudes of P and S waves radiated by the source were equal (uniform P and S radiation). For simulating the effect of the receiving characteristics for vertical and horizontal geophones on the input wavefield were independently generated PP, SS, PS and SP incident x-t seismograms and introduced in the eqs. (6)-(7).

The Figs. 5a, b show the PP and SS seismograms without receiving geophone characteristics. Here the incident S waves have zero point at certain offsets, followed by a 180° phase shift for large offsets. It is associated vertical and horizontal records are shown in the Figs. 5c, d as would be recorded by realistic 3C geophones. All P and S arrivals shown up on both records. The shallow SS-2 reflection appears interfering the PP-5 reflection and showing the expected behavior for pure S waves on both records (Fig. 2).

The result of the $\tau$-p P/S separation applied on both vertical and horizonttal records is indicated in the Figs. 5e, f, using near-surface velocities $V_p$= 1,500 m/s and $V_s$= 650 m/s, as correspond to the velocities for the first layer in the synthetic model.

The comparison of the filtered pass-P and pass-S records with the incident seismograms shows a very good performance of the P/S separation filter recovering to the original PP and SS seismograms without any interference (SS-2 and PP-5 reflections). Only minor remnant amplitudes of the removed wavetypes are left on each record for near offsets after the P/S separation and could be explained for errors of the $\tau$-p transform due to the truncation of the events in the x-t domain. Some noise is present on both pass-P and pass-S records as consequence of the limitations during the summation process in the $\tau$-p domain for obtaining the inverse x-t sections, associated with a intrinsic limitation of the summation process in the $\tau$-p domain and the limitations included in the filter coefficients calculation.

The effect on the performance of this P/S separation filter considering wrong estimates of the near-surface velocities $V_p$ and $V_s$ is shown in the Fig. 6a, d. It is obvious that the final quality of both records is deterioreted as consequence of increments in the real $V_p$ and $V_s$ values associated with the first layer of the Dankbaar model. A very bad separation is obtained for a increment of 250 m/s (Fig. 6c, d). Although it is possible to observe certain degree of separation among PP and SS waves, strong remnant amplitudes associated with these waves are left on the pass-P and pass-S records which indicates a bad performance of the separation filter $F_v^p$, $F_v^s$, $F_h^p$ and $F_h^s$. In particular, the pass-P record appears more affected than pass-S one showing important alterations on the slope of the PP events.

The behavior of the coefficients $F_v^p$, $F_v^s$, $F_h^p$, and $F_h^s$ for different values of the near-surface velocities $V_p$ and $V_s$ is shown in the Figs. 7a, d. It is evident the anomalous behavior for $F_v^p$ and $F_h^s$ in comparison with $F_v^p$ and $F_h^s$ whose values are less than 2. As consequence, the relations that express the pass-P and pass-S wavefield (eqs. (8) - (9)) are strongly affected altering the coupled relation between both equations. The ideal situation is indicated in the Fig. 7d where the coefficients are acoted between -1 and +1. The additional condition on slowness p values for PP waves ($\leq$ 0.63 s/Km for horizontal incidence) limits the behavior for $F_v^p$ and $F_h^p$.

The next example represents a case which is more problematic in separating P and S waves. Now converted PS and SP reflections are also included. Since we have a horizontally layered earth model, PS and SP reflections have equal slowness and traveltimes at all offsets.

The Figs. 8a, b show the incident P- (PP and SP) and incident S- (SS and PS) waves. The SP converted reflections have quite low amplitudes whereas the converted PS waves have large amplitudes. The vertical and horizontal geophone records resulting from the incident P and S waves are shown in the Figs. 8c, d. On the vertical geophone the converted reflections 2 and 3 have zero amplitudes due to the destructive interference of PS and SP. On the horizontal geophone record all PP and converted reflections show up next the SS reflections.

The resultants filtered pass-P and pass-S (Figs. 8e, f) were compared with the incident seismograms (Figs. 8a, b). It is evident a good agreement between the corresponding records. The incident P and S waves are retrieved correctly, although SS-2 and SS-3 appear with low amplitudes after the filtering process.

In the Figs. 9a, d is shown the effect on the filtering process when it is used a wrong estimation of the near-surface velocities $V_p$ and $V_s$, for the separation of the vertical and horizontal records in Figs. 8c, d.

The last example includes a real case from a potential stratigraphic production area in Venezuela. The Figs. 10a, b show the vertical and horizontal raw records acquired using 3C geophones along a 2D testing line in this area. It is evident the strong effect of the ground roll that interfers the P and PS data interpreted at 2 - 3 sec and 3.3 - 4.5 sec, respectively. This data was acquired using dynamite as P source. The largest offset is 3672 m, with a geophone separation of 17 m.

The filtered records pass-P and pass-S corresponding to both raw records are shown in Figs. 11a, b. Using Vp= 1,700 m/s and Vs= 700 m/s obtained from the first breaks analysis on the raw data. Although the analysis of the raw data indicates a low superposition between P and PS waves, it is evident the good performance of the P/S separation filter in isolating the principal P and PS events. Some remnant PS in the pass-P data between 3.4 - 3.6 sec at large offsets. In the same record appears several reflections between 4 - 5 sec that are not evident on the vertical raw record. The analysis of the slopes associated with these reflections seem to indicate any relation with converted waves observed at the same window time on the pass-S record.

## COMPARISON TO F-K P/S SEPARATION FILTER

The results obtained from this study was compared with the results published by Dankbaar using f-k transformation for separating P and S waves with synthetic data. The Figs. 12a, h show the comparison between the filtered pass-P and pass-S records applying both methods. The analysis of these results not indicates sustancial differences using the $\tau$-p domain for mode separation. Although the amplitudes of some S waves, i.e. SS-3, are more attenuated after the $\tau$–p than f-k P/S separation filters. This fact along some noise level present in the records could indicate some limitations in the reconstruction from $\tau$–p domain to x-t domain for certain slowness p values.

It is important to point out that there is a difference in polarity for the PS waves between both results, this changes in polarity are introduced by the modelling package (Uniseis) which use different convention or algorithms for generating the PS waves syntehtic data (Fig. 8a, b) of those used by Dankbaar for developing his synthetic seismograms.

## CONCLUSIONS

1.- The P/S separation filter in the $\tau-p$ domain had proved very good performance on synthetic data showing different degrees of superposition of P and S arrivals.

2.- The filter appears stable with respect to errors in the selection of the values of near-surface Vp and Vs velocities, but the pass-P filtered record seems to be more sensible than pass-S filtered record.

3.- The use of $\tau$-p within the process let us eliminate noise like ground-roll, perhaps we don't need to apply previous filtering to the data before entering to the P/S separation filter.

4.- The results obtained from the use of the P/S separation filter in $\tau$-p domain on real data show its applicability and robustness into the 2D sequence of converted wave processing and its future application in 3D data.

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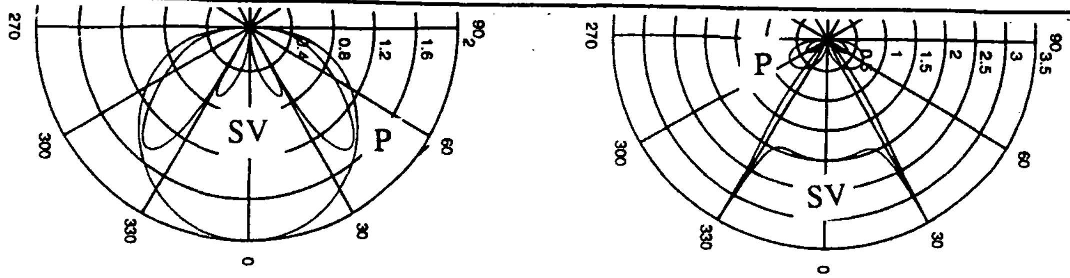
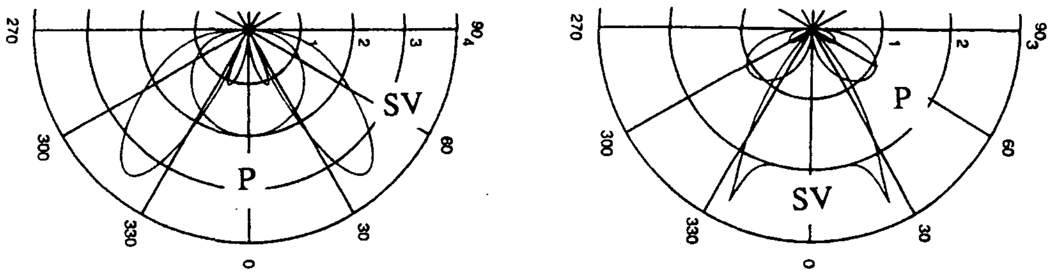


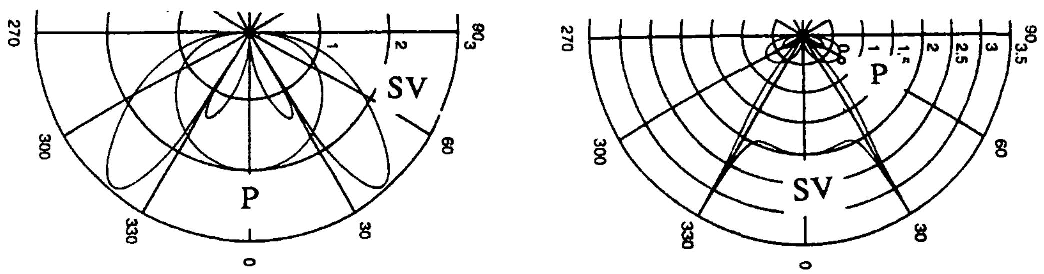

(a) (b)

Considering Vp= 1,200 m/s and Vs= 600 m/s




(a) (b)

Considering Vp= 1,900 m/s and Vs= 800 m/s




(a) (b)

Considering Vp= 2,000 m/s and Vs= 1,000 m/s

Fig. 1. Receiving characteristic (polar diagram) of vertical geophones (a) and of horizontal geophones (b) for P waves and for SV waves as a function of angle of incidence for different values of Vp and Vs velocities.

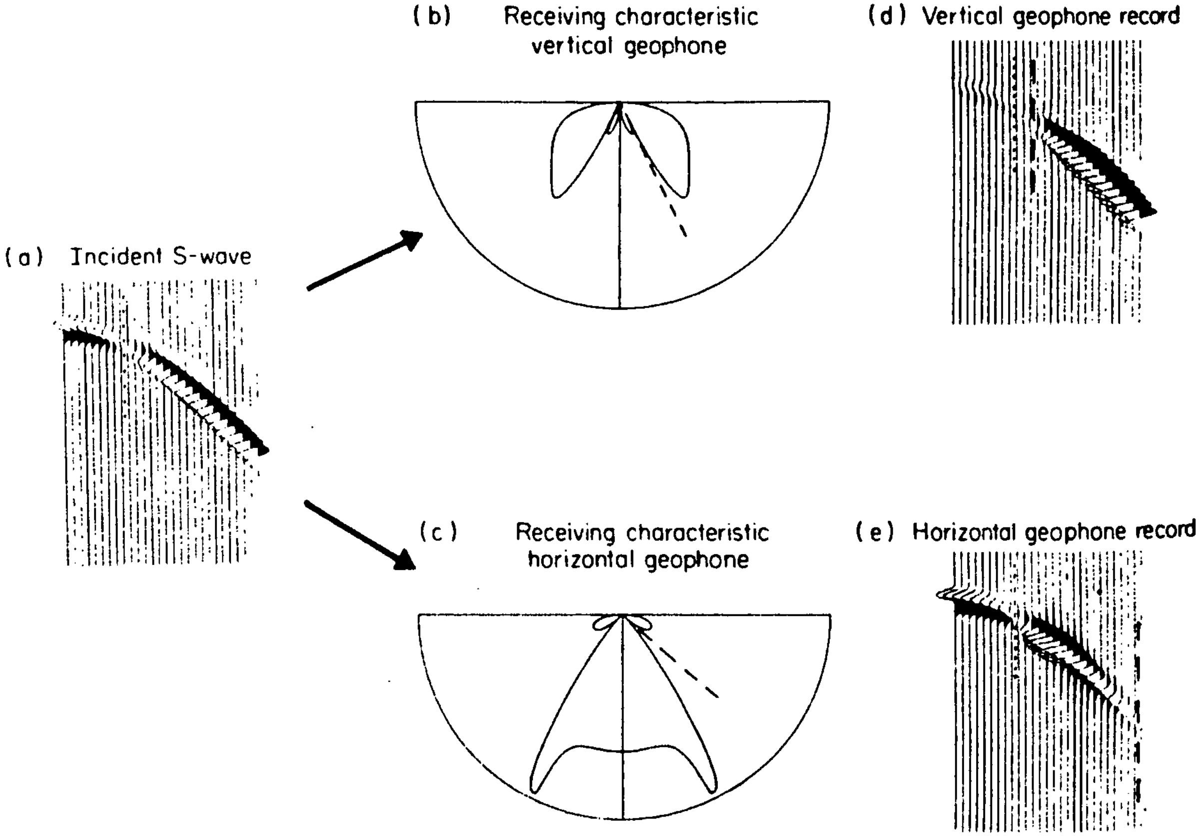



Fig. 2. Effect of receiving characteristic on an incident SV wave.
(a) SV wave incident at the surface for equidistant offsets,
(b) and (c) receiving characteristics of vertical and horizontal geophones,
(d) and (e) shearwave as recorded on vertical and horizontal geophones (From Dankbaar, 1985).

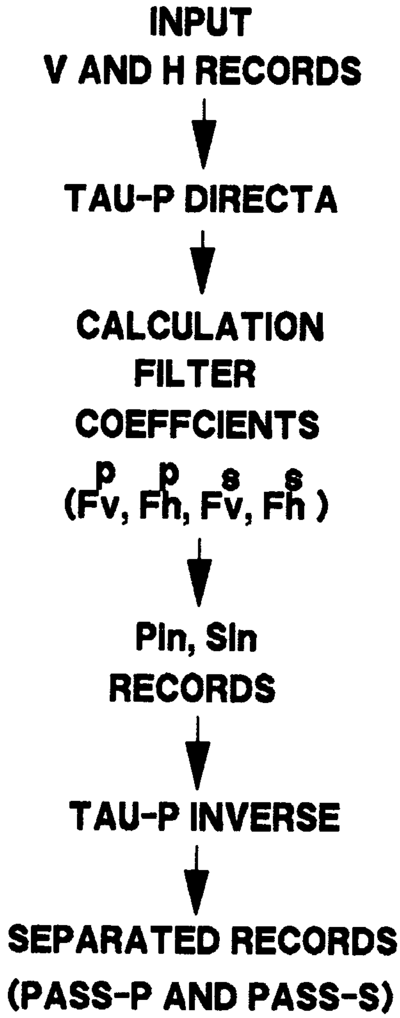



Fig. 3. Flowchart of the P/S separation filter in the tau-p domain.

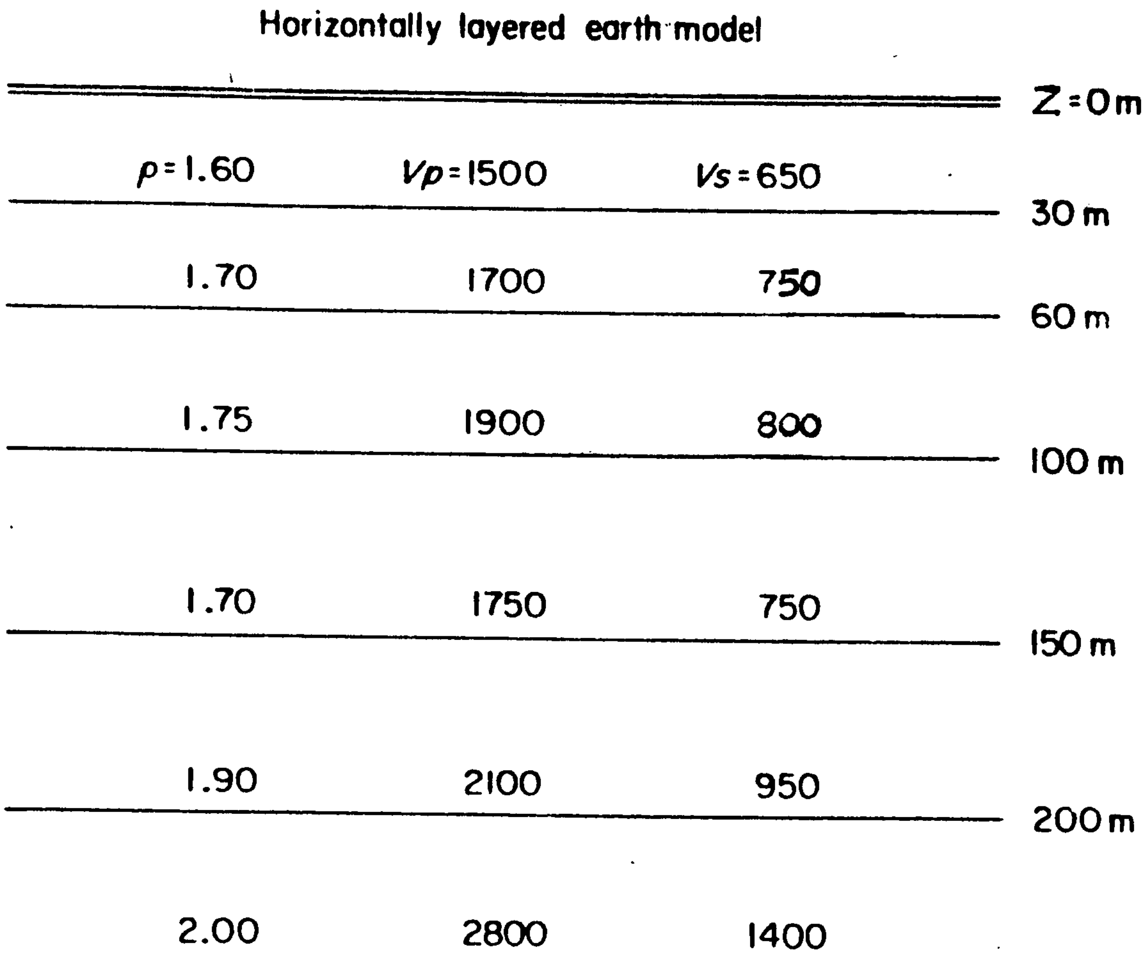



Fig. 4. Subsurface model used for syntehtic data calculation (From Dankbaar, 1985).

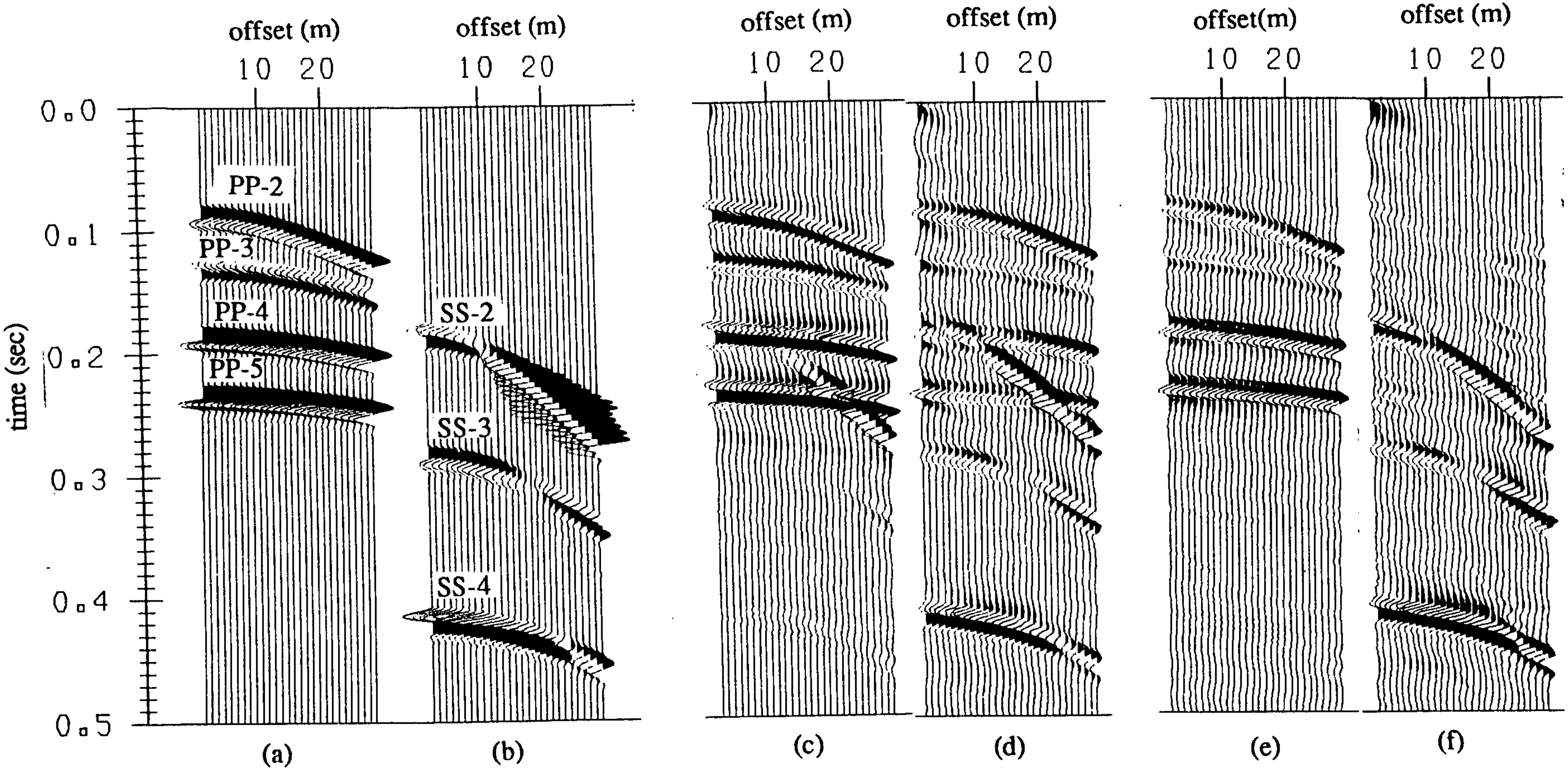



Fig. 5. (a) Record of incident PP reflections, with no receiving characteristics.
(b) Record of incident SS reflections, with no receiving characteristics.
(c) Record from single vertical geophone resulting from incident PP and SS reflections.
(d) Record from single horizontal geophone resulting from incident PP and SS reflections.
(e) The resultant filtered pass-P section obtained from the P/S separation applied on both vertical and horizontal records (Figs, 5c, d), using Vp= 1,500 m/s and Vs= 650 m/s.
(f) The resultant filtered pass-S section obtained from the P/S separation applied on both vertical and horizontal records (Figs. 5c, d), using Vp= 1,500 m/s and Vs= 650 m/s.

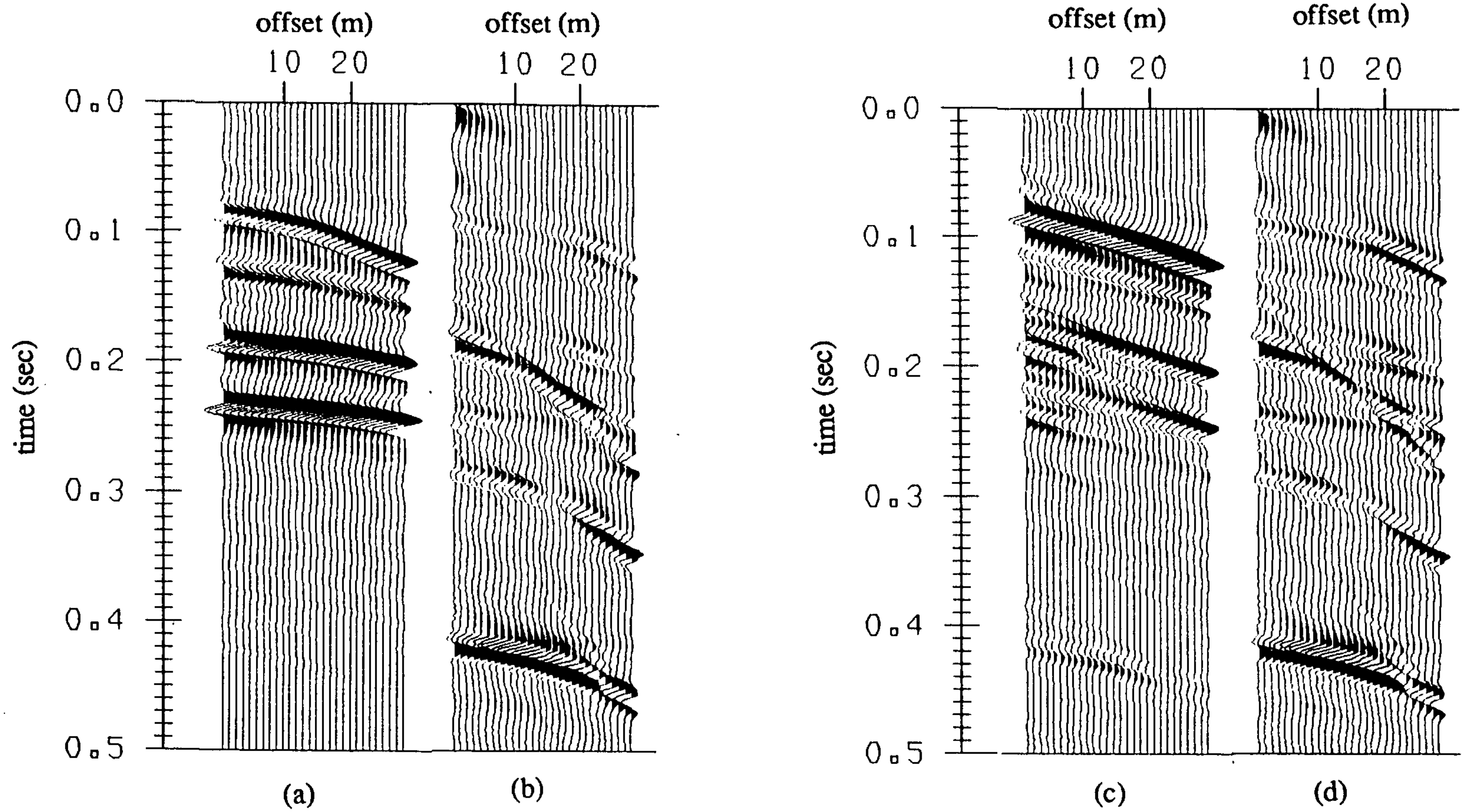



Fig. 6. (a) Filtered pass-P record obtained using Vp= 1,600 m/s and Vs= 750 m/s.
(b) Filteres pass-S record obtained using Vp= 1,600 m/s and Vs= 750 m/s.
(c) Filtered pass-P record obtained using Vp= 1,750 m/s and Vs= 900 m/s.
(d) Filtered pass-S record obtained using Vp= 1,750 m/s and Vs= 900 m/s.

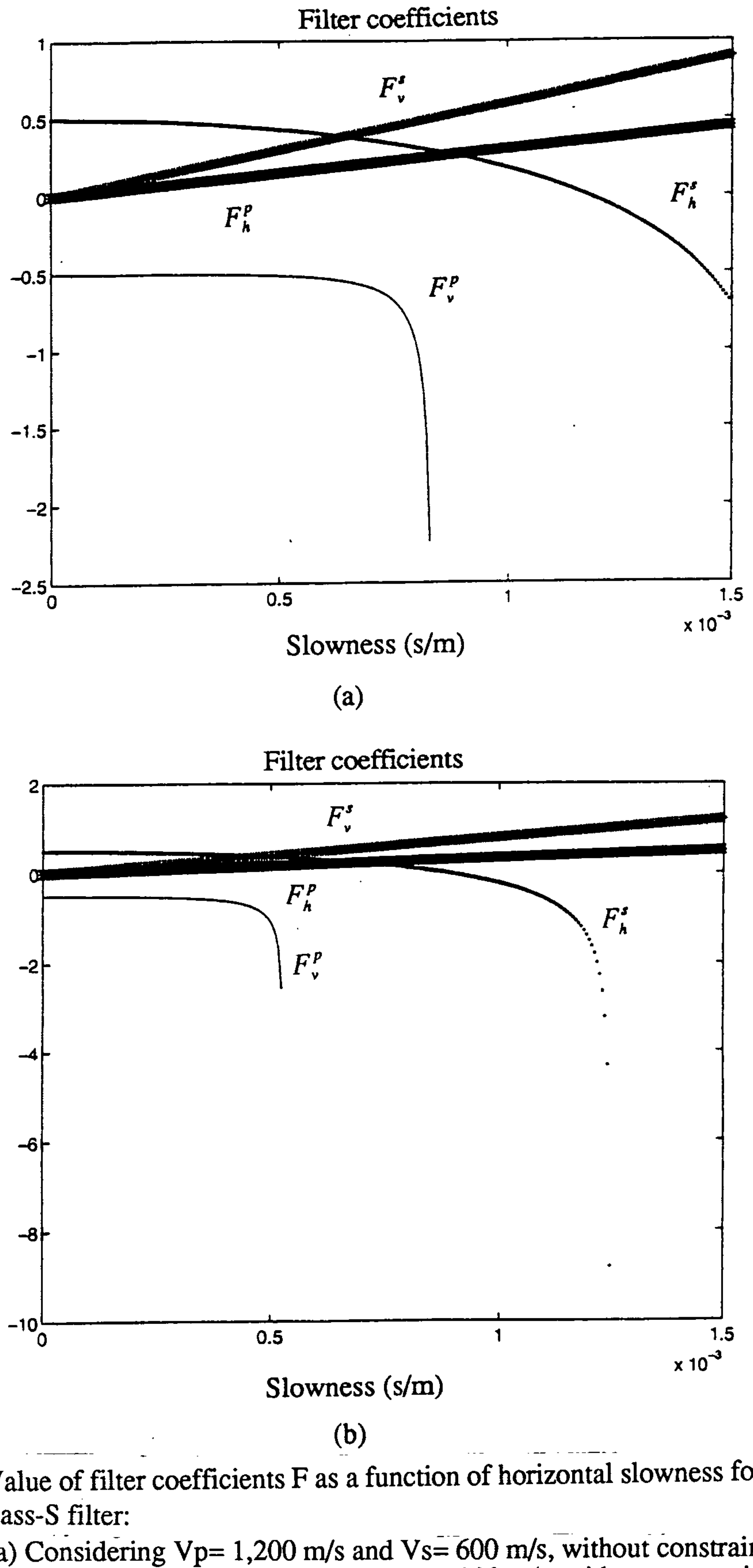
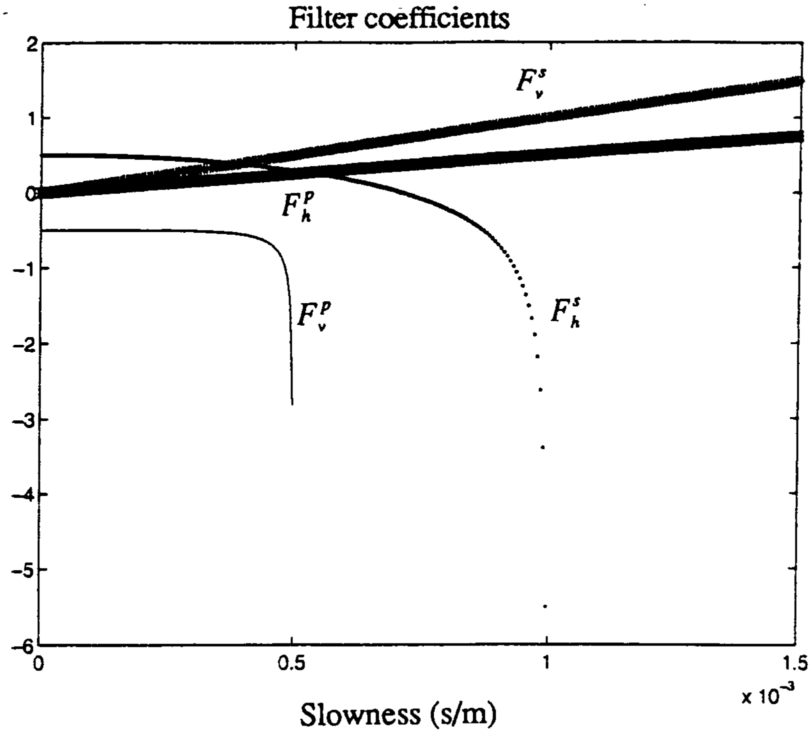
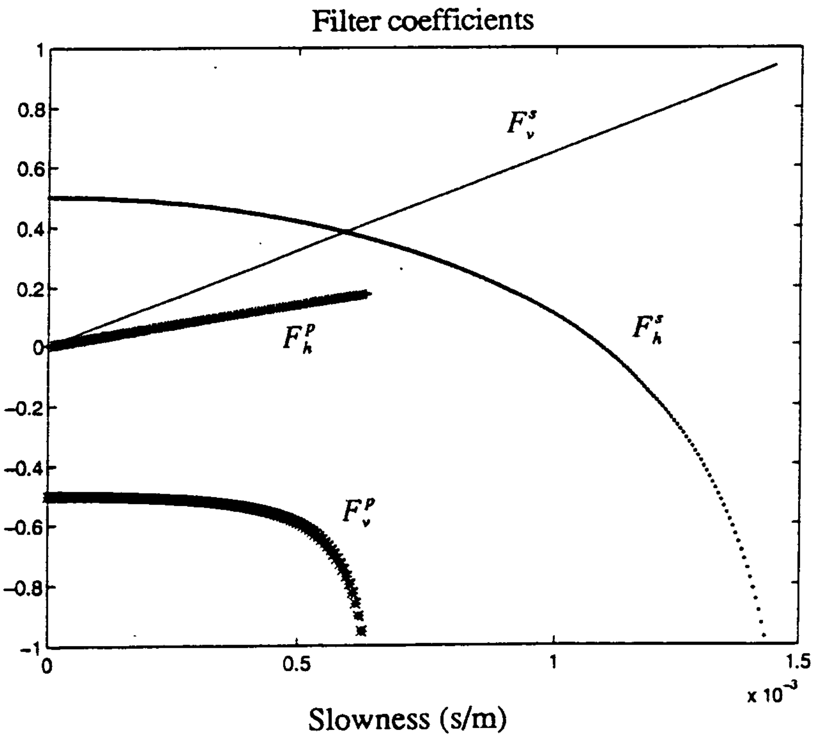



Fig. 7. Value of filter coefficients F as a function of horizontal slowness for pass-P and pass-S filter:
(a) Considering Vp= 1,200 m/s and Vs= 600 m/s, without constrains.
(b) Considering Vp= 1,900 m/s and Vs= 800 m/s, without constrains.




(c)




(d)

Fig. 7. Value of filter coefficients F as a function of horizontal slowness for pass-P and pass-S filter:
(c) Considering Vp= 2,000 m/s and Vs= 1,000 m/s, without constrains.
(d) Considering Vp= 1,500 m/s and Vs= 650 m/s with constrains.

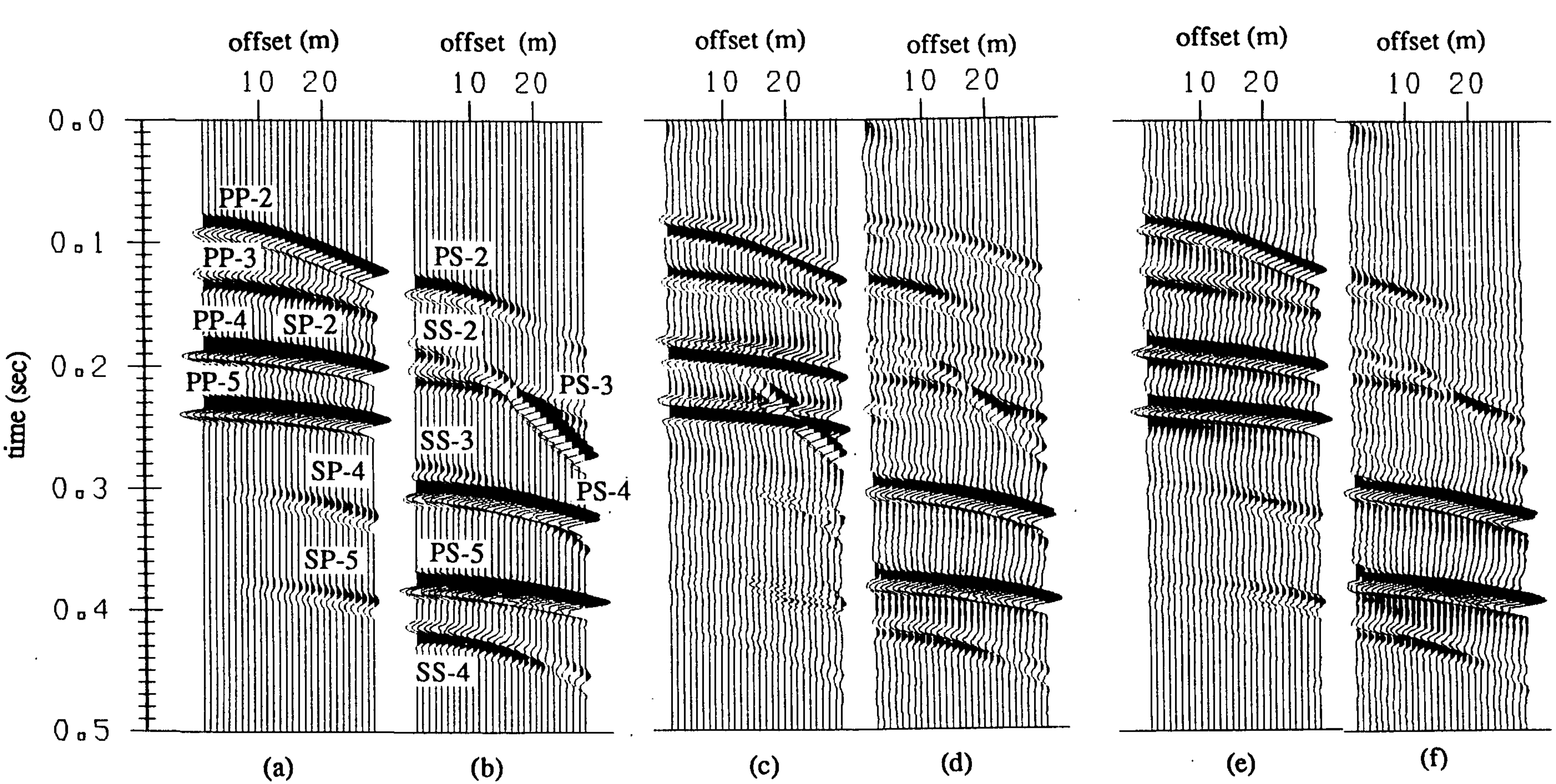



Fig. 8. (a) Record of incident P- (PP and SP) reflections, with no receiving characteristics.
(b) Record of incident S-(SS and PS) reflections, with no receiving characteristics.
(c) Record from single vertical geophone resulting from incident PP, SS, PS and SP reflections.
(d) Record from single horizontal geophone resulting from incident PP, SS, PS and SP reflections.
(e) The resultant filtered pass-P section obtained from the P/S separation applied on both vertical and horizontal records (Figs. 8c, d), using Vp= 1,500 m/s and Vs= 650 m/s.
(f) The resultant filtered pass-S section obtained from the P/S separation applied on both vertical and horizontal records (Figs. 8c, d), using Vp= 1,500 m/s and Vs= 650 m/s.

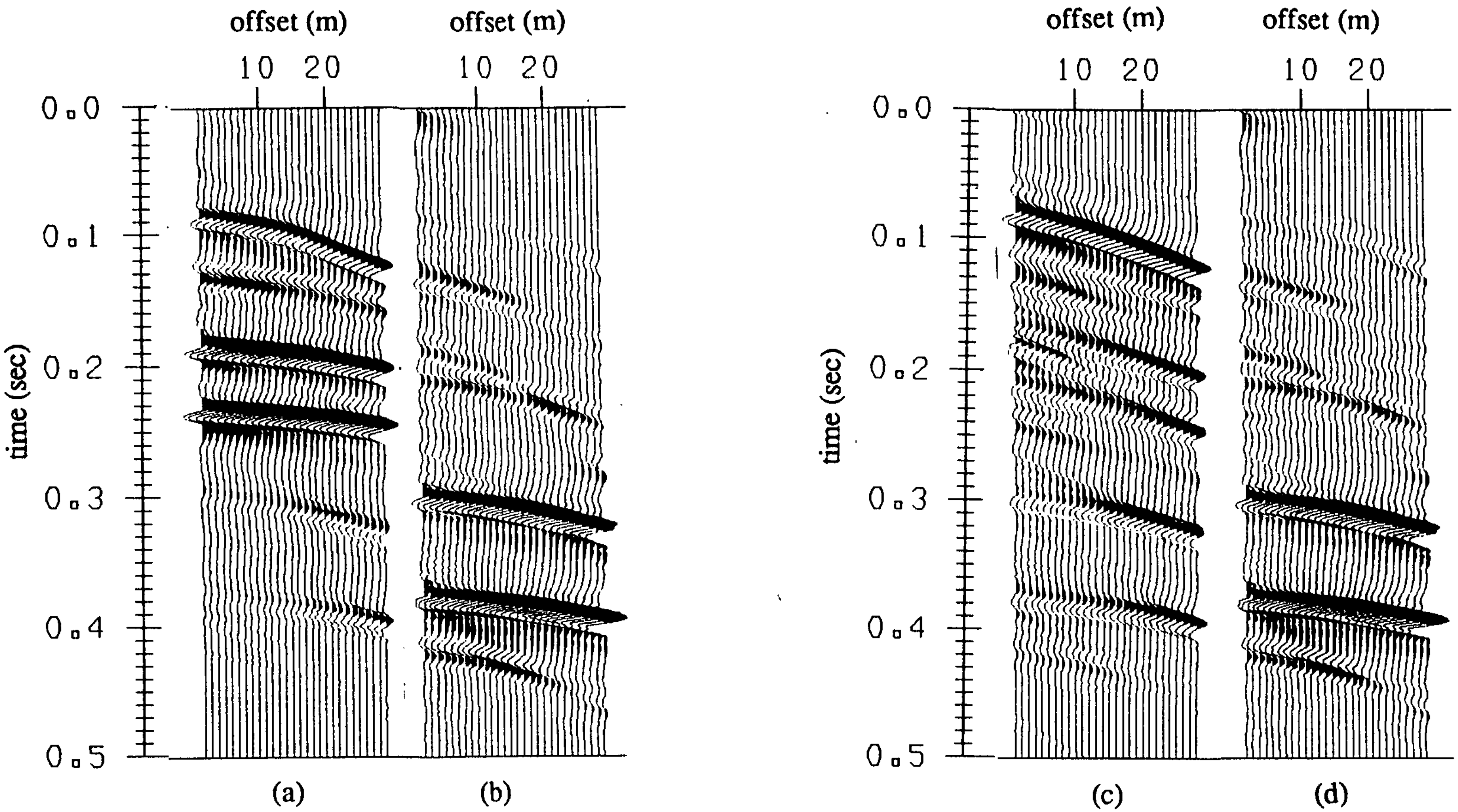
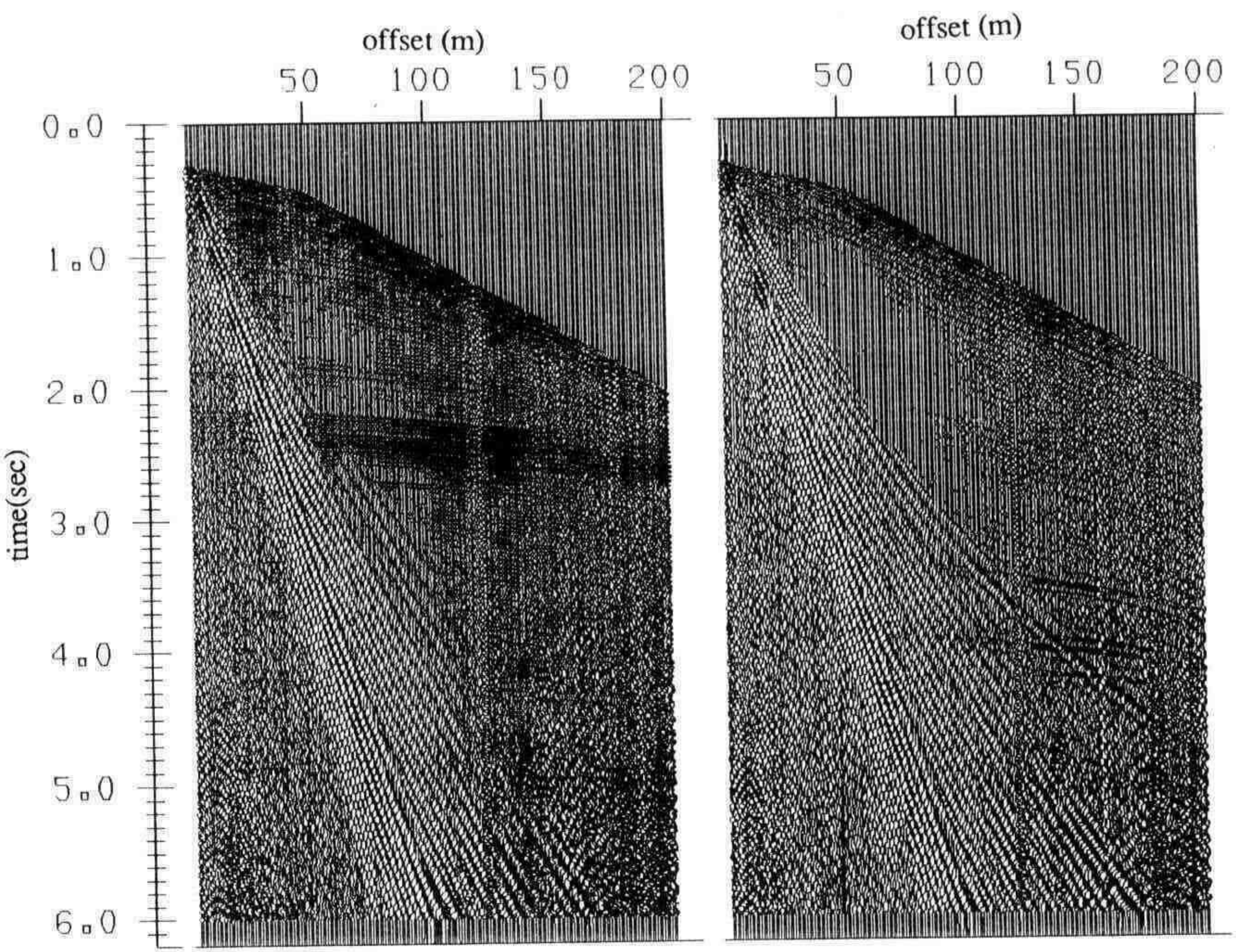



Fig. 9. (a) Filtered pass-P record obtained using Vp= 1,600 m/s and Vs= 750 m/s.
(b) Filteres pass-S record obtained using Vp= 1,600 m/s and Vs= 750 m/s.
(c) Filtered pass-P record obtained using Vp= 1,750 m/s and Vs= 900 m/s.
(d) Filtered pass-S record obtained using Vp= 1,750 m/s and Vs= 900 m/s.




(a) (b)

Fig. 10. (a) Vetical raw record acquired in Venezuela.
(b) Horizontal raw record acquired in Venezuela

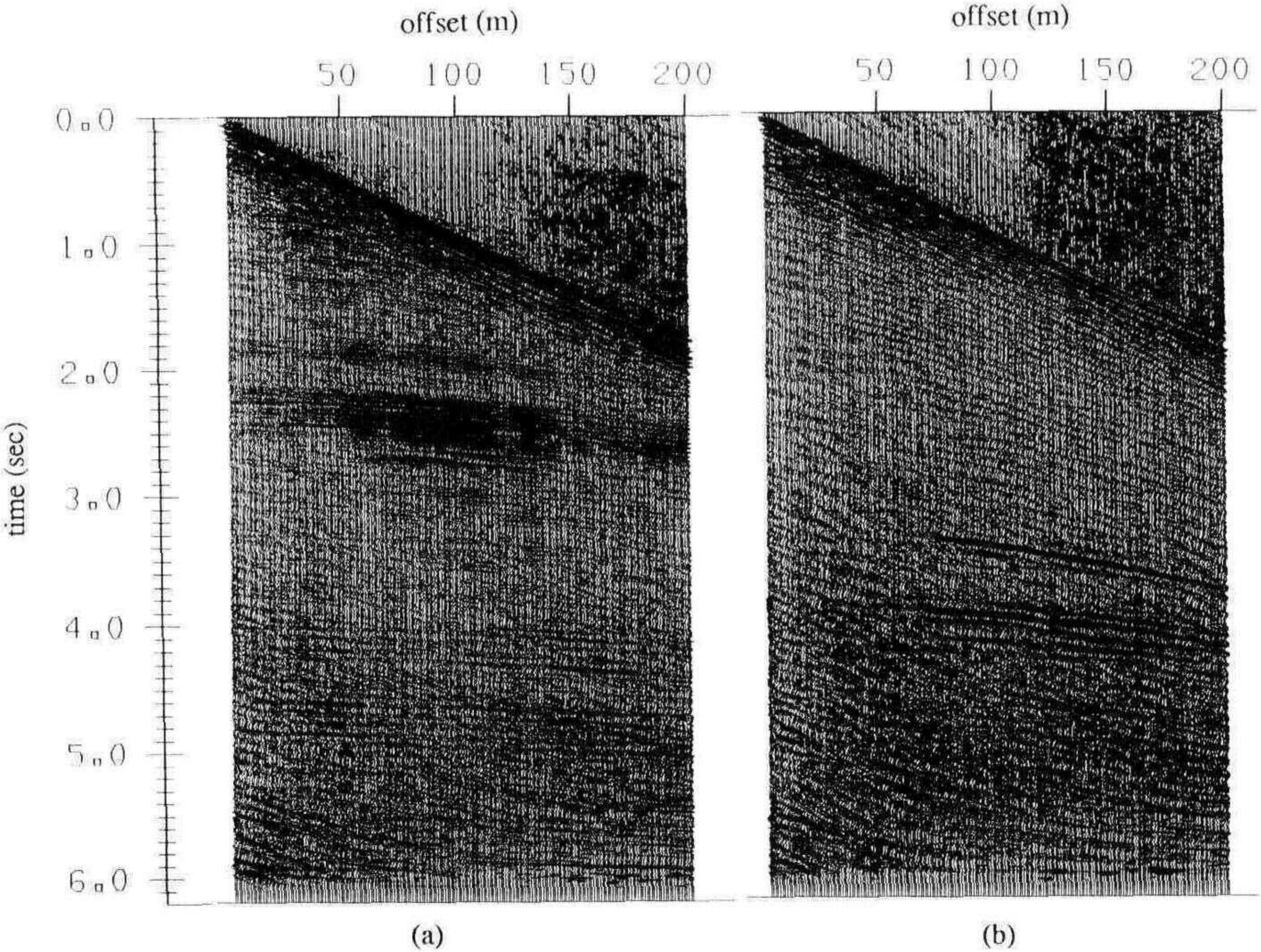



Fig. 11. (a) Filtered record pass-P corresponding to both raw records shown in Fig. 10a, b.
(b) Filtered record pass-S corresponding to both raw records shown in Fig. 10a, b.

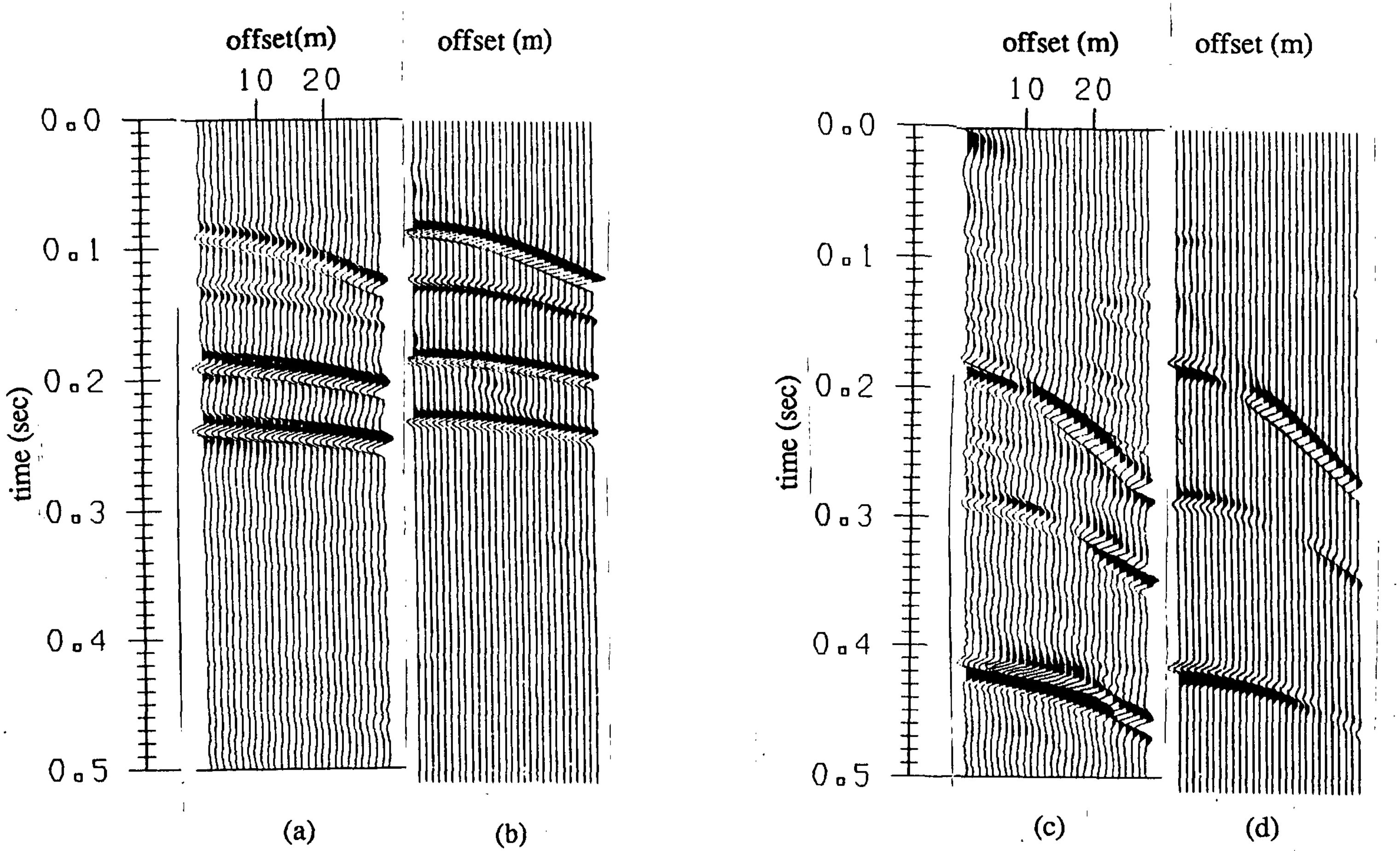
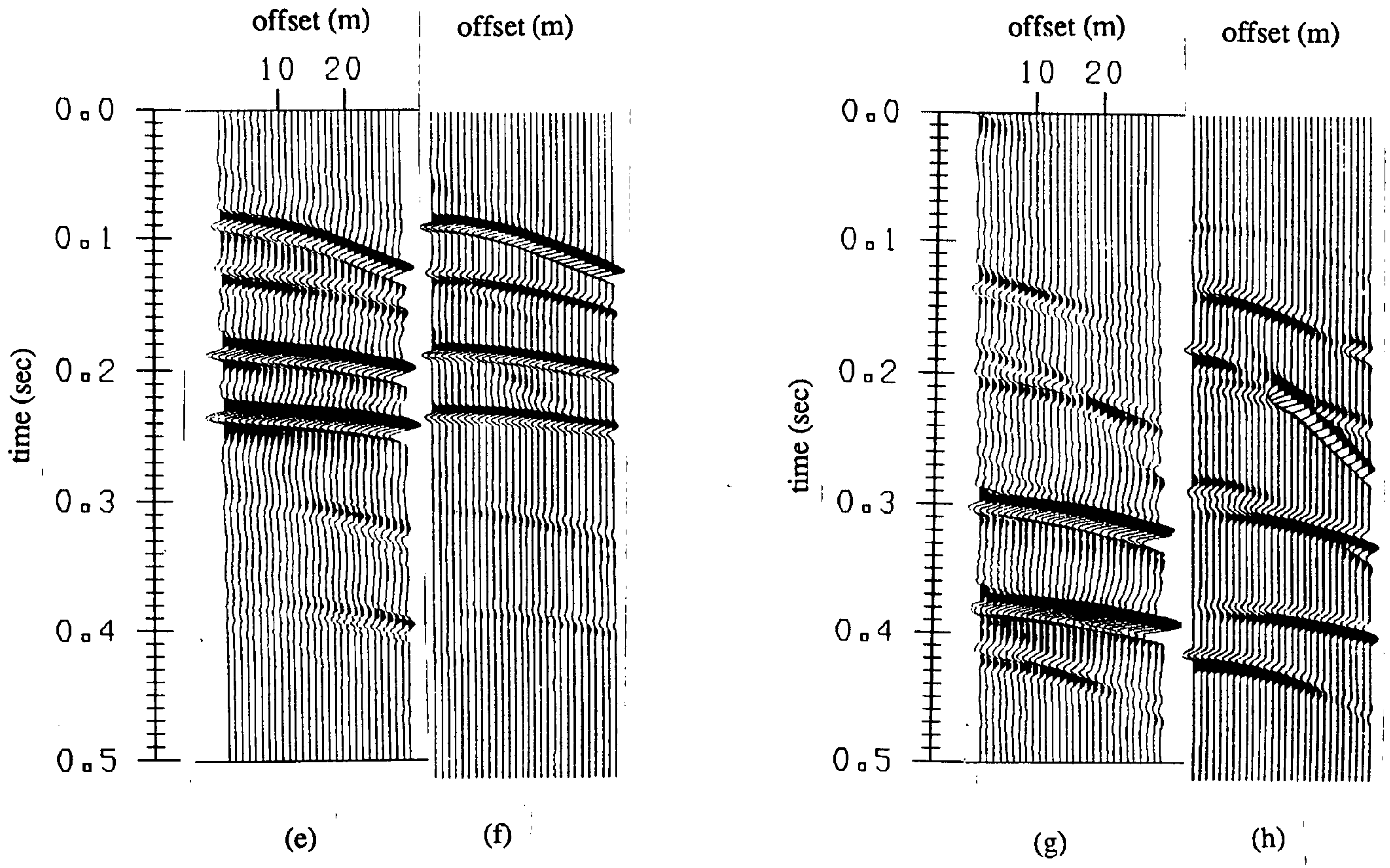



Fig. 12. (a) Filtered pass-P record for incident PP and SS reflections obtained using tau-p P/S separation filter.
(b) Filtered pass-P record for incident PP and SS reflections obtained using f-k P/S separation filter (Dankbaar method).
(c) Filtered pass-S record for incident PP and SS reflections obtained using tau-p P/S separation filter.
(d) Filtered pass-S record for incident PP and SS reflections obtained using f-k P/S separation filter (Dankbaar method).




(e) Filtered pass-P record for incident PP, SS, SP and PS reflections obtained using tau-p P/S separation filter.
(f) Filtered pass-P record for incident PP, SS, SP and PS reflections obtained using f-k P/S separation filter (Dankbaar method).
(g) Filtered pass-S record for incident PP, SS, SP and PS reflections obtained using tau-p P/S separation filter.
(h) Filtered pass-S record for incident PP, SS, SP and PS reflections obtained using f-k P/S separation filter (Dankbaar method).