Separation of *PSP*-waves on marine seismic data

Georgy Mitrofanov, IGG /SB RAS, Russia
Viatcheslav Priimenko, LENEP/UENF, Brazil

Abstract

There is considered a possibility of selection of signals associated with the *PSP*-waves using surface observations, which are obtained during the usual marine seismic survey. The method is based on an algorithm, using *a priori* information about the model of medium, which allows us to apply the ray tracing procedure and to identify corresponding waves. This makes it possible to determine the time intervals, which can contain signals reflected from the target horizon. These intervals are used in the selection of *PSP*-waves. Such selection involves a transform performed for optimal observation bases, which corresponds to the largest amplitudes of target signals. To increase the stability of the *PSP*-waves selection, possible caustic singularities are eliminated by analyzing values of the KMAH index.

Introduction

Practical use of converted waves in the analysis of various characteristics of the elastic media has become increasingly important in recent years. The obtained information is crucial for determining the elastic parameters and the anisotropic properties of the media.

Analysis of the horizontal displacements is so important that in shelf regions specifically for the registration of such displacements (and posterior separation of the converted waves) were developed bottom geophones. However, using the bottom geophones or ocean bottom cables with multi-receivers in the deep bottom survey is associated with considerable difficulties. Therefore makes sense to consider special processing methods, which allow determining information on converted waves using one-component survey at the ocean surface. Such information is contained in the reflected converted *PSP*-waves with not much more complex nature than the usual *PS*-waves used in the ground survey. Our preliminary studies of this question, using an efficient algorithm for the simulation of wave fields for the elastic models (Mitrofanov at al., 2009), have confirmed this possibility. They showed that for the vertical component of the converted *PS*-wave, reflected from a target horizon, there are distances, where their strength is not inferior to the intensity of the reflected *PP*-wave observed at the appropriate times. Thus, there is a good perspective for the selection of the *PSP*-waves using data of the surface marine seismics in the deep ocean.

PSP-waves extraction process can be done in different ways. In our opinion, the following two approaches may be perspective. The first is based on the ray tracing schemes and nonsymmetrical trace gathers, which take into account differences in the converted arrival times. The second uses the original data migration to the ocean bottom at the velocity of longitudinal waves, with subsequent extraction of converted waves. Both approaches can be equivalent in the case of the horizontal sea bottom. Their effectiveness may depend only on the level of other types of signals on the original and migrated sections for the times, where the selected converted waves can be presented. But in the case of the curved bottom, each of these approaches will have their own advantages and disadvantages. We examine the possibility of *PSP*-waves picking on the basis of an algorithm related to the first of these approaches. The algorithm makes it possible a substantial reprocessing of available surface marine seismic data, for the regions in which *a priori* models of the medium can be constructed. Selected signals help clarify the characteristics of target horizons, for example, by effectively solving the inverse dynamic problems for thin-layered elastic media models.

Method

By now there exists a sufficiently large number of different algorithms, designed to separate the longitudinal, transverse, and converted waves. All such algorithms, conditionally, can be divided into three major groups. As a basic principle in determining the membership of the algorithm to a particular group performs degree of using *a priori* information about the medium.

- The first group includes algorithms based only on the original data and its structure. The algorithms do not use *a priori* information about the medium, or use it in small quantities. These algorithms include the coherent summation algorithm by oblique samples (Puzyrev, 1979; Nefedkina et al., 1980). In its implementation can be done search by two parameters: t_0, γ, where t_0 is the arrival time corresponding to the zero source-receiver distance, and $\gamma = V_S / V_P$. This algorithm is similar to obtaining velocity spectra in the selection of *PP*-waves.
- The second group uses a polarizing feature and information about the medium near the border, where the seismic receivers are situated. This group includes all of the proposed up to now algorithms of the *f-k* filtering and $\tau - p$ transformation (Dankbaar, 1985; Chiburis et al., 1988).

- The third group of algorithms is based on the maximum use of available *prior* information about the medium, where the various types of waves are propagated; for example, using information about the velocity of wave propagation for the entire medium. This group includes the *LSMF* algorithm (Nemeth, 1996), as well as true amplitude migration algorithms and CFP operators (Goldin, 1991; Hubral et al., 1996; Bolte, 2003).

According to the above classification, the algorithm proposed for separating the *PSP*-waves should be referred to the third group, because of it uses as much as possible *a priori* information about the model of medium. This approach, in our opinion, is reasonable when converted waves are required to refine the model representations with respect to a specified area of the medium, where the target objects are situated, for instance, productive horizons. Such problems are typical for 4D seismics or for performing detailed seismic studies.

Before we proceed to description of the algorithm we state conditions under which it must operate. The conditions are formulated according to the results of previous studies, and based on the analysis of existing algorithms for selection of the converted *PS*-waves.

- Presence of significant background noise events, which have regular character and in their properties (arrival times, spectral characteristics, etc.) may be close to the target *PSP*-waves.
- Identification of areas with the highest overgrowth of the amplitudes for the target converted waves, which capable of producing maximum signal-to-noise ratio (*SNR*) in their selection.
- Determining the area of possible caustic singularities of converted waves in order to eliminate the effect of such features on the efficiency of the selection of target waves.

Working with the algorithm it is also assumed that the *a priori* model of the medium is known with some accuracy. Obviously, the accuracy and detailing of the model may be different. The greatest detail consists in the maximum number of reflecting boundaries and values $\mathrm{V_P}, \mathrm{V_S}, \rho$ (or functions $\mathrm{V_P}(x,y)$, $\mathrm{V_S}(x,y)$, $\rho(x,y)$) in each of the layers. The smallest one consists in function smoothing $\mathrm{V_P}(x,y)$ and $\mathrm{V_S}(x,y)$ in the entire domain between the surface of observations and lower reflecting boundary. The precision and quality of selecting target waves will depend on the accuracy of *a priori* model.

<u>The main ideas</u>. They are associated with using the second mixed derivatives of the *PSP*-wave hodograph. Such derivatives are utilized for two purposes: firstly, for accelerating the solution of direct problems and secondly, for identifying areas with caustic singularities in the converted waves. In order to achieve the second objective we use the KMAH index, see (Mitrofanov and Priimenko, 2013).

Mixed derivatives of the hodograph can significantly accelerate in the two-point problem the process of the construction of rays $R(s,r)$ for different types of waves, when the positions of the source s and receiver r are fixed. Along with this, a double effect is reached consisting in determination of the ray parameter, which defines the required ray and guarantees the approximation of the hodograph of the considered wave. For non-converted waves the algorithm was proposed in (Kurdyukova, 1993), and its effectiveness has been demonstrated on various complex models (Mitrofanov and Kurdyukova, 1999). We generalize such approach on the case of converted waves. It is based on the shooting method, which reduces the complex two-point problem of the ray tracing to a sequence of much simple one-point problems with the given values of ray parameter.

In the first step, there is constructed a set of reference rays for a fixed boundary and the giving type of wave, outgoing from point s with a fixed step with respect to the angle variable. Building a network of supporting rays is particularly effective if we have a large number of observations, i.e., the parameters (s,r) can have considerable variations. Then, from the totality of reference rays we select two rays that have the closest outgoing on the surface points from the left and right side of the receiver r. Using the standard shooting procedure we can find two rays with outgoing on the surface points, most closed to the receiver point r of angles of approach of the rays. Between angles of approach for the two selected rays there is realized the linear interpolation to find angle ν_0, corresponding to a receiver point r_0. The angle obtained is used later as an initial approximation to determine a new ray $R(s,p)$, defined by its ray parameter $p_0 = \mathrm{V_P}^{-1} \sin \nu_0$.

Directly, the shooting of a ray consists in the solution of the following equation

$$x(p) - r = 0, \tag{1}$$

where $x = x(p)$ is the output point of the seismic ray, defined by parameter *p*, on the observations surface. Eq.(1) can be solved using the Newton method, when to find *j*-iteration of *p* there is used the following expression

$$p_{j+1} = p_j - (\partial(x(p_j))/\partial p)^{-1} \cdot (x(p_j) - r) \tag{2}$$

with $j = 0,1,2,...$.

Taking into account that the ray parameter can be represented in the form (Goldin, 1986)

$$p = \partial(t(s,r))/\partial s,$$

where $t(s,r)$ is the hodograph of the corresponding wave, we obtain

$$\left(\frac{\partial x(p_j)}{\partial p}\right)^{-1} = \frac{\partial p}{\partial x} = -\frac{\partial^2 t(s,r)}{\partial s\, \partial x} = -\frac{\partial^2 t(s,r)}{\partial s\, \partial r} \quad (3)$$

because for horizontal surface x-coordinate coincides with *r*. Substituting Eq. (3) into Eq. (2) we have the following equation to find p_{j+1} approximation of *p*

$$p_{j+1} = p_j + \frac{\partial^2 t(s,r)}{\partial s\, \partial r}\left(x(p_j) - r\right)$$

with $j = 0,1,2,\ldots$.

In the case of converted wave travel time curve, the second order mixed derivative is calculated by the formula represented in (Mitrofanov and Priimenko, 2013).

Thereby, the second order mixed derivative gives a possibility to determine a new angle ν_{j+1} of the output of the ray from point s for the solution of the next one-point problem. The construction of such solutions is carried out up to $|r - x(p)| < \varepsilon$ with a prescribed tolerance $\varepsilon > 0$. As a rule, the iteration process converges rapidly even for the case of complex models and it is necessary only a few iterations to determine the target ray with tolerance $\varepsilon = 0,05$ m.

At practical realization of the method most difficulties are associated with a many-valuedness of hodograph $t(s,r)$, which occurs due to curved boundaries. In this case, solving the corresponding initial problem we shall obtain different rays, due to "jump" to another branch of the ray. This feature complicates the convergence of Newton's method. In addition, further difficulties occur in the identification, isolation and treatment of the corresponding waves. For such cases, there is used the analysis of the values of KMAH index. Based on it, we can find all the rays corresponding to a given pair of points (s,r).

Structure of the basic algorithm. The structure may be divided in the following three elements.

1. Construction of rays $R^{\mathrm{PS}}(s,p)$ on the basis of *a priori* values of the parameters of the model for the fixed boundary and giving positions of sources and receivers. There are used the values of the second mixed derivative of *PS*-wave hodograph.
2. Specification the following values for the target *PS*-wave: arrival time $t^{\mathrm{PS}}(s,r;\varsigma)$, amplitude $A^{\mathrm{PS}}(s,r;\varsigma)$, and KMAH index. It is also used the mixed second derivative of the hodograph. On the basis of these parameters there are determined the time intervals and observations, where the target wave can have the greatest amplitude growth, and where such wave has no caustic singularities.
3. Using the temporal and spatial intervals, selected from the original seismograms based on the values of $t^{\mathrm{PS}}(s,r;\varsigma)$, for $\tau - p$ transformation. Then, we define the target components on the basis of the generalized linear inversion in the $\omega - p$ domain, similar to the work (Cary, 1998).

Such scheme can significantly increase the stability of *PSP*-waves selection. This is done by several important reasons: firstly, the construction of ray schemes and amplitudes can get the results that are not inferior to ones, obtained by the algorithms of migration in true amplitudes or *LSMF*; secondly, the algorithm makes it possible to perform a selection of the target waves in the most appropriate areas for this seismogram; and thirdly, using the hodograph leads to greater efficiency for converting into $\omega - p$ domain that allows the best way to separate the target waves from other types of waves, both with respect to the spectral composition and kinematic shifts. Of the above it follows that realization of this scheme provides the fulfillment of conditions for extracting the target waves that have been formulated earlier.

Note that the algorithm can be used to select both the converted *PSP*-waves, which can be observed by streamer acquisition data, and the *PS*-waves, that can be observed by *OBC* seismic data. Depending on the data it has to be taken into account that as an output we can obtain either the polarized *S*-wave components or only the vertical component of *P*-wave. Also be aware that for the second part of ray $R^{\mathrm{S}}(s,r)$ (related to the reflected *S*-wave propagating from a reflection point to the receiver r) in the case of surface marine data it is required using a composite code for the last layer of the *a priori* model.

Results

Testing the proposed algorithm was conducted on 2D models, which were built using real data corresponding to an offshore oil field. Various *a priori* information, obtained using the marine streamer and OBC data (and also well data), was used during the construction of models. Based on this information, it was built a few models, corresponding to certain OBC lines. The structure one of the models is shown in Fig. 1. The constructed models served as the basis for calculating synthetic seismograms by different methods. The spread area is shown by green color. Examples of seismograms are presented in Fig. 2. A part of real seismic data was used as a noise component, which had been added to the synthetic data. This way gives a possibility to guarantee the presence of target signals and bring synthetic data to real ones. Examples of the part of real data and synthetic seismograms are shown in Fig. 3.

According to the structure of proposed algorithm there were selected time intervals, which may contain the target converted waves. The $\tau - p$ transformation and determination of the components of target waves was done for the selected intervals. The resulting components were presented in the form of the original time intervals.

The performed experiments have shown that in the process of separation of the reflected *PSP*-waves it is essential the optimal selection of such intervals. The optimal selection is particularly important for caustic areas and in the presence of significant noise. It allows, even in the case of the large *SNR* values, to get a considerable overgrowth of the target signal in $\tau - p$ domain and to guarantee stable selection of the target wave components based on the inverse algorithm.

Examples

Fig. 4 shows the selected intervals containing the signals corresponding to the *PSP*-wave reflected from horizon *h-MIn* (Fig. 1). These signals, named as *PSP-2*, were identified in the synthetic data, (Fig. 3(b)). Under identification and selection of the intervals we used the calculated values $t^{\mathrm{PS}}(s,r;\varsigma)$ of the arrival times for corresponding wave.

Comparison of the intervals, corresponding to different *SNR*, indicates that in the case of significant *SNR* values the target signals are weak, even taking into account their arrival times. This was also evidenced by the results of $\tau - p$ transformation. However, despite this the proposed algorithm can in fact distinguish the target signal in all domain of observation, maintaining its dynamic features (Fig. 5).

In a more complex case of selecting signals corresponding to the *PSP*-wave reflected from the horizon *h-Mac* (Fig. 1), where a caustic was presented, the wave field was of an even more complex. Therefore, just only using the KMAH-index allowed performing the correct selection of intervals (see Fig. 6(a)). As a result, we succeeded in the identification of the target signals (Fig. 6(b)).

Conclusions

The results obtained suggest the following. If an *a priori* model, constructed on the basis of processing and interpretation of the *PP*-waves, has sufficient accuracy, then the proposed algorithm can identify the target converted *PSP*-waves even in the case of a sufficiently high level of noise events.

References

1. **Bolte J.F.B. 2003.** Estimation of focusing operators using the common focal point method. PhD thesis, Delft University of Technology.
2. **Cary P.W. 1998.** *P/S* Wavefield Separation in the Presence of Statics. CREWES Research Report, Vol. 10, p. 30-1 to 30-8.
3. **Goldin S.V. 1986.** Seismic Traveltime Inversion. Investigations in Geophysics, Society of Exploration Geophysics.
4. **Goldin S.V. 1991.** To the theory of seismograms transform into depth and time sections. In: Methods of Calculation and Interpretation of Seismic Wave Fields. IGG SB AS USSR Press, Novosibirsk, 5-44. (in Russian)
5. **Hubral P., Schleicher J. & Tygel M. 1996.** A unified approach to 3D seismic reflection imaging, part I: Basic concepts. Geophysics, 61, 742-758.
6. **Kurdyukova T. 1993.** Methods of acceleration of direct problems solutions for complex media (two-dimensional problem). Geology and Geophysics (Soviet), 34(4), 99-107.
7. **Mitrofanov G. & Kurdyukova T. 1999.** Algorithms of ray tracing for block media. SEG 69th Annual Meeting, Expanded abstracts.
8. **Mitrofanov G., Priimenko V., Misságia R. & Amaral L. 2009.** Utilização das transformadas de Laplace e Fourier-Bessel na modelagem de meios elásticos delgados. Revista Brasileira de Geofísica, 27(2), 205-224.
9. **Mitrofanov G. & Priimenko V. 2013.** Use of KMAH index in seismic data processing. In: 13th International Congress of the Brazilian Geophysical Society & EXPOGEF, 2013, Rio de Janeiro.
10. **Nefedkina T., Kondakova G., and Olejnik L. 1980.** Digital processing of converted reflected waves. Geology and Geophysics (Soviet), 21(4), 66-67.
11. **Puzyrev N.N. 1979.** Time Fields of Reflected Waves and Method of Effective Parameters. Nauka, Novosibirsk. (in Russian)

Acknowledgments

This work was supported by the Petrobras Institute for Research and Development - CENPES, RJ, Brazil. The first author is especially thanks to the North Fluminense State University Darcy Ribeiro - UENF, RJ, Brazil, for providing support as a visiting researcher at LENEP/CCT/UENF

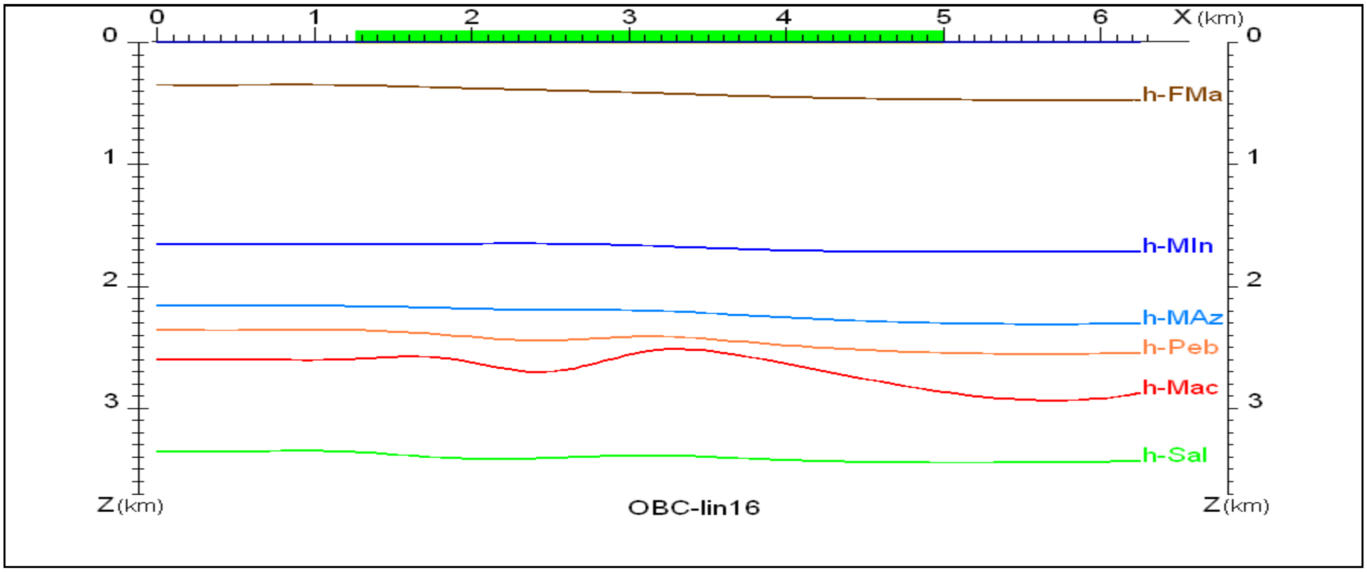

Figure 1. Structure of model

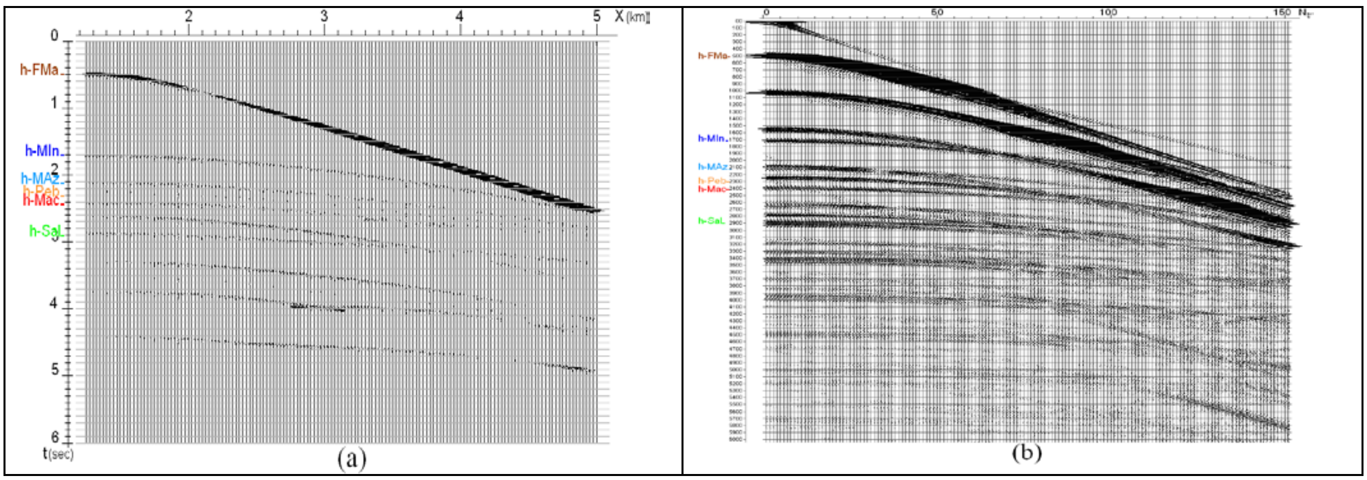

Figure 2. Seismograms calculated using the ray tracing (a) and finite-difference (b) methods

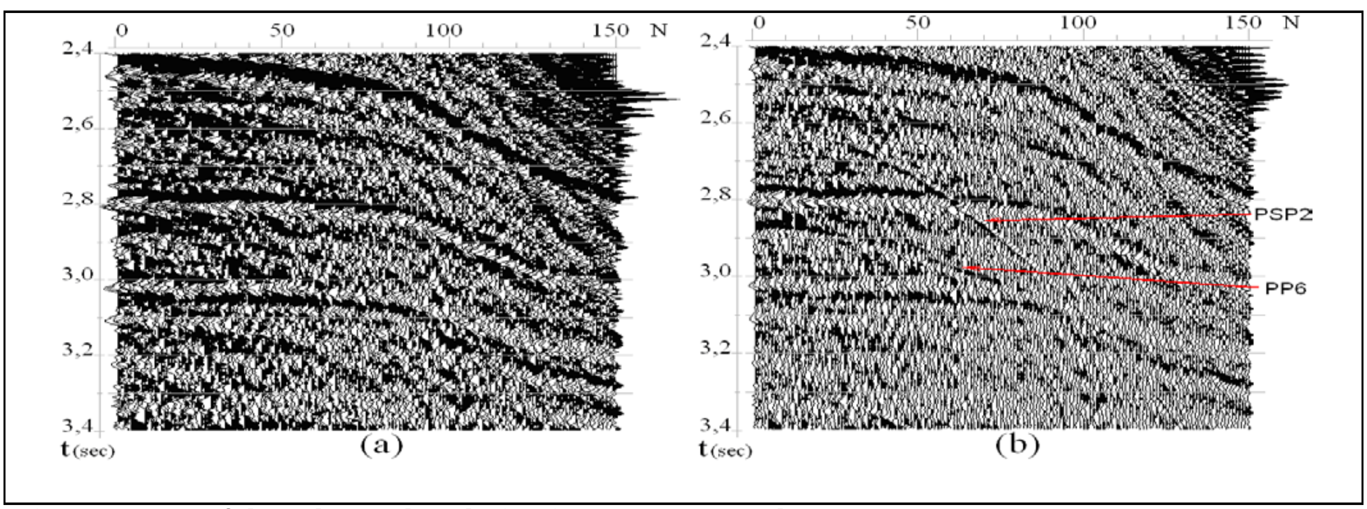

Figure 3. A part of the real (a) and synthetic seismograms, *SNR*=1(b)

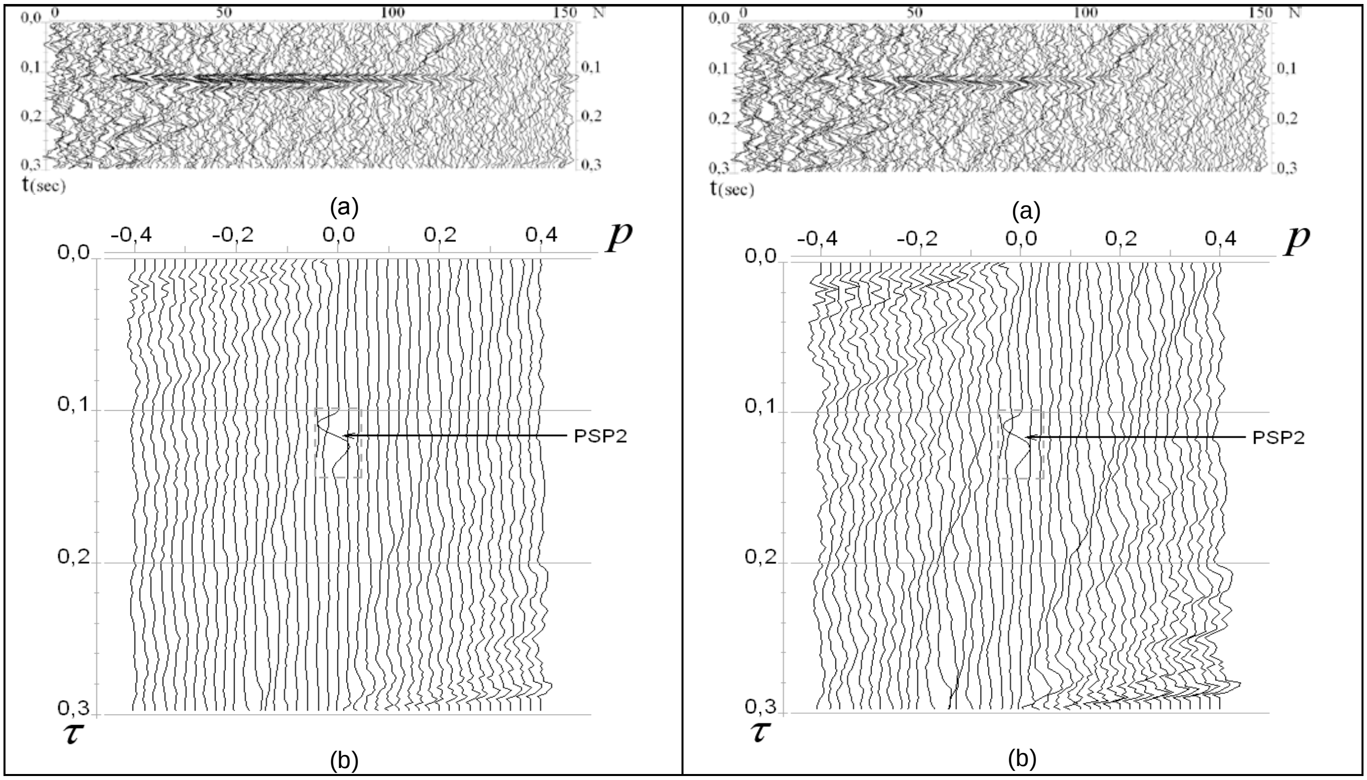

Figure 4. Selected parts of the traces (a) and selection of the *PSP2* reflection in $\tau - p$ domain (b): *SNR*=2 (left column) and *SNR*=1 (right column)

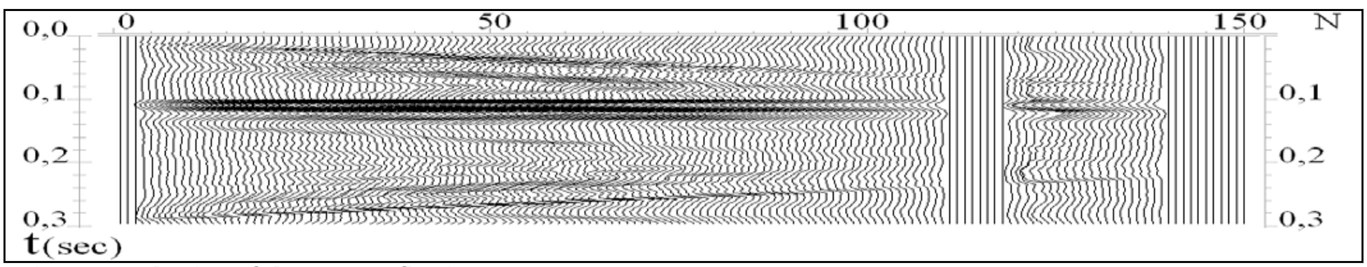

Figure 5. Selection of the *PSP2* reflection, *SNR*=1

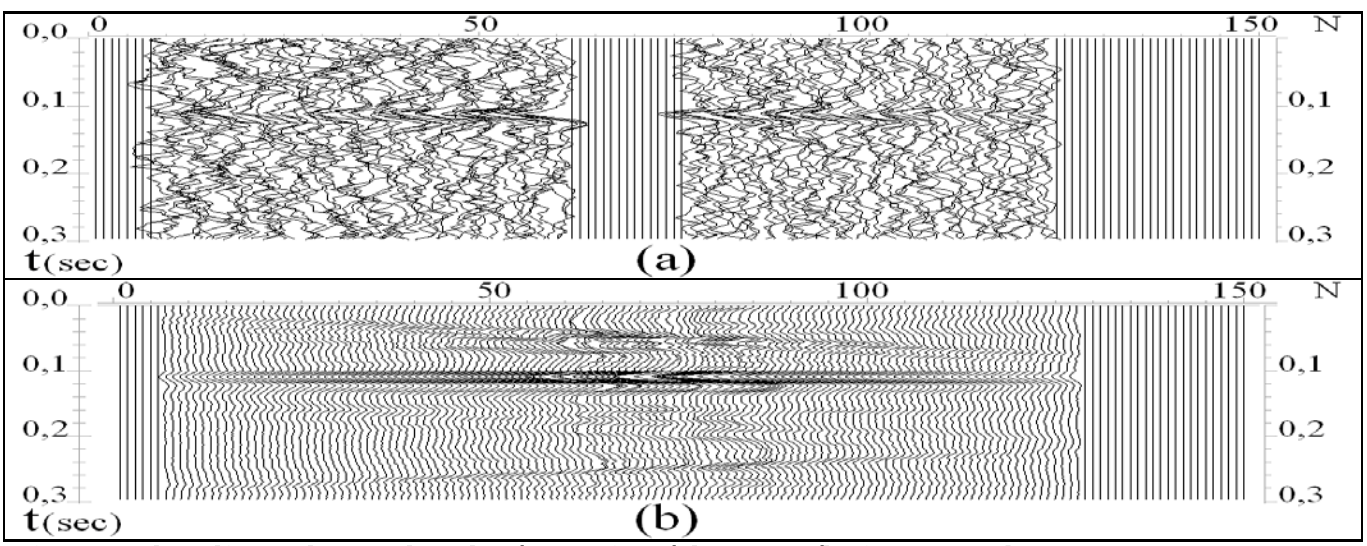

Figure 6. Selected intervals (a) and results of extraction of the *PSP5* reflection, *SNR*=1 (b)