Principles and Techniques of VSP Data Processing

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ABSTRACT

Vertical seismic profiling (VSP) is a popular seismic exploration technology that has been confirmed to be really efficient for solution of various geological problems even in very complicated conditions. The way to achieve this and take all of the VSP advantages (such as efficient velocity model recovery, direct impulse shape estimation and zero-phase deconvolution, detailed surface-borehole tie, high-resolution imaging and dynamic inversion) is to implement correct processing techniques.

In this paper we present key principles of VSP data processing yielded and inherited as a result of more than 40 years experience in borehole seismic. These principles form the concept of model based processing technology which includes state-of-the-art developments and is aimed at high quality and reliability of the acquired results. Demonstrated case histories show examples of efficiency of the presented technology of VSP data processing.

INTRODUCTION

Vertical seismic profiling invented in 1960s by E.I. Galperin has become a useful tool of subsurface exploration, and it's now widely used for detailed research of hydrocarbon reservoirs both as independent method and in combination with surface seismics. The key advantage of VSP surveys is possibility to directly obtain layer velocities and source impulse shape. VSP also allows registration of full vector multi-wave response of the medium, anisotropy detection, dynamic inversion, and high resolution imaging with the use of both P and converted S waves. However, all these becomes possible if VSP data are properly processed. The paper discuss basic principles of VSP data processing aming at getting all their advantages.

PREPROCESSING

Raw data quality estimation and wavefield editing should be performed at the preprocessing stage. So the following procedures should be applied:

- Quality estimation: signal-to-noise ratio calculation for different frequency ranges.
- Moment mark statics correction.
- In the presence of reference geophone record: shot point conditions heterogeneity compensation. (This implies statics correction and signal's form standardization).
- First break hodograph determination. (Three-component traces or their modules should be used).
- Polarization parameters calculation and wavefield orientation. The latter allows preliminary separation of different waves based on their polarization.

KINEMATIC PROCESSING

At this stage kinematic properties of the medium are calculated. 2D velocity model is derived as a result of kinematic inversion of all available arrival times which may include not only direct wave hodographs recorded for different shot point offsets, but also clearly correlated hodographs of waves of other types (Stepchenkov et al., 2005). In this case both P- and S-wave velocities may be calculated. Otherwise, S-wave velocities may be determined by iterative approach comparing synthetic and real arrival times of converted waves. Then average and interval velocities of P and S waves are calculated.

Fig.1.A shows vertical hodographs, average, interval and layer velocities for both P and S waves, calculated from VSP data. Fig.1.B. represents an example of model building for several shot points (SP). It implies velocity model optimization by first break hodographs from all SP. As a result, we get a single model that should be used for further processing.

WAVEFIELD DECOMPOSITION

It is the wave field separation procedure that mainly affects the quality of VSP data processing results. This procedure must primarily preserve dynamic features of target waves. This can be met by following some common principles which are given below.

Additivity

The core meaning of the *additivity* principle is that actual *separation* of a vector wave field is carried out, not just extraction of specific waves.
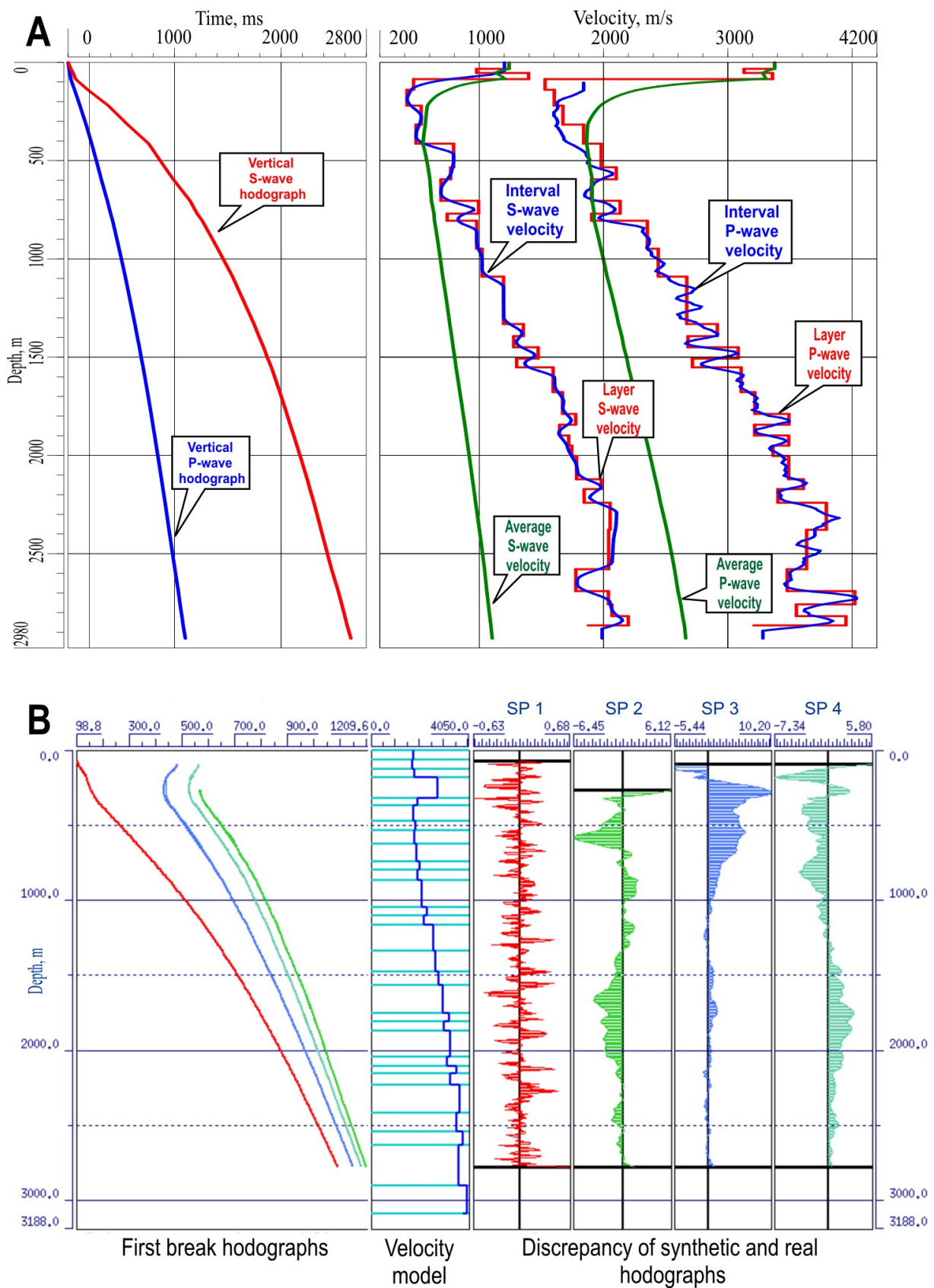
Fig.1 Kinematic procesing: A – kinematic parameters of the medium; B – velocity model derivation using fist break hodographs for several shot points.

After each wave field transformation (i.e. noise reduction, wave subtraction) both the result of the procedure and the residual should be saved. The residual can always be derived by subtracting the output from the input. Thus, as wave field separation is finished, one will have a set of various components of the raw seismic section: target wave fields of different types, artefacts and unwanted waves (such as tube waves and casing vibrations), incoherent noises (for example, harmonic and spike noise) as well as the residual wave field obtained after subtraction of all referenced components. Having all these results, one is free to restore the original wave field or refine any of the components at further stages of processing by additional filtering or adjustment of wave parameters (travel time and polarization) and keeping in mind that undesirable energy must be always transferred to noise and residual wave fields.

Fig. 2 shows an example of the proposed wave field decomposition technique. Fields of irregular noise (harmonic noise, etc.), downgoing and upgoing P waves, downgoing and upgoing converted PS waves, tube waves and residual field are presented.

Reference velocity model use

The principle of the *model-based processing* is yielded from the following aspects. According to conventional VSP processing workflow, when approaching to the wave field separation stage, velocity model of the medium should already be derived as a result of kinematic inversion of available arrival times. This velocity model can be implemented during initial wave field separation. Based on the known velocity model, vector wave field may be (1) transformed to a wave directed ("tracking") component where the most of target wave energy resides (Ferentsi et al., 2003); (2) flattened (via NMO correction procedure) which makes the subtraction of target waves easier as their initial hodograph may be defined just as a vertical line in the time-depth domain. Such techniques become extremely important when trying to discriminate waves with similar apparent velocities and polarization parameters (for instance, upgoing converted PS waves and upgoing PSS waves; PSS denotes monotype SS reflection generated by downgoing converted PS wave).

Iterative approach

The *iteration* principle is implemented in the wave field separation procedure as sequential subtraction of different types of waves in order of their decreasing energy and further adjustment of their parameters when other waves are absent and thus interference is reduced.

At first iteration of target wave selection large spatial aperture for estimation of average impulse shape must be defined for better discrimination from other waves. After the first iteration selected wave fields almost do not contain waves of inappropriate types. On the other hand, true parameters of target waves are distorted (averaged along depth axis), and a part of their energy is left in the residual field. Then each extracted wave field should be added to the residuals and after adjustment of wave and velocity model parameters subtracted again on the narrower spatial base. Such a process is repeated while any coherent events can be indicated in the residual wave field.

DECONVOLUTION

Zero-phase deconvolution based on the direct wave impulse is the next stage of processing. The ultimate principle here is the maximum expansion of available frequency band accounting for a given signal/noise ratio. Fig. 3 displays an example of downgoing and upgoing wave field deconvolution. Amplitude spectrum of upgoing waves after deconvolution ranges from 8 to 150 Hz.

Deconvolution should be applyed to all selected waves as well as to residual wavefield. Increase in resolution often leads to disclosing of some coherent noise in selected waves or target waves in residals. Therefore waves' refinement should be performed after deconvolution by extra interations of wavefield decomposition procedure.

FINAL PROCESSING

The final result of zero-offset VSP data processing is primary reflection trace used for surface sismics tie to borehole data. Primary reflection trace is obtained by reflected wavefield orientation into follow-up component, its transforming to two-way travel times and stacking in a sliding window. It should be noted that the sliding stacking may be used only when transforming to two-way travel times makes target waves' hodograpgs strictly vertical that means we have exact velocity model. If there is just an approximate model, primary reflection trace may be obtained by special technique of seismic boundaries' angles estimation in near vicinity of a well (Tabakov et al., 2004).

At the final stage of processing of zero- and near-offset VSPs dynamic inversion is usually carried out. When dealing with only P waves, optimal inversion for acoustic impedance recovery can be applied (Tal-Virsky, Tabakov, 1983). In the

Initial wave field

Extracted component

Residual

Time, ms

DP -
downgoing P waves

DPS -
downgoing PS waves

UP -
upgoing P waves

UPS -
upgoing PS waves

Tube -
downgoing tube wave
and corresponding
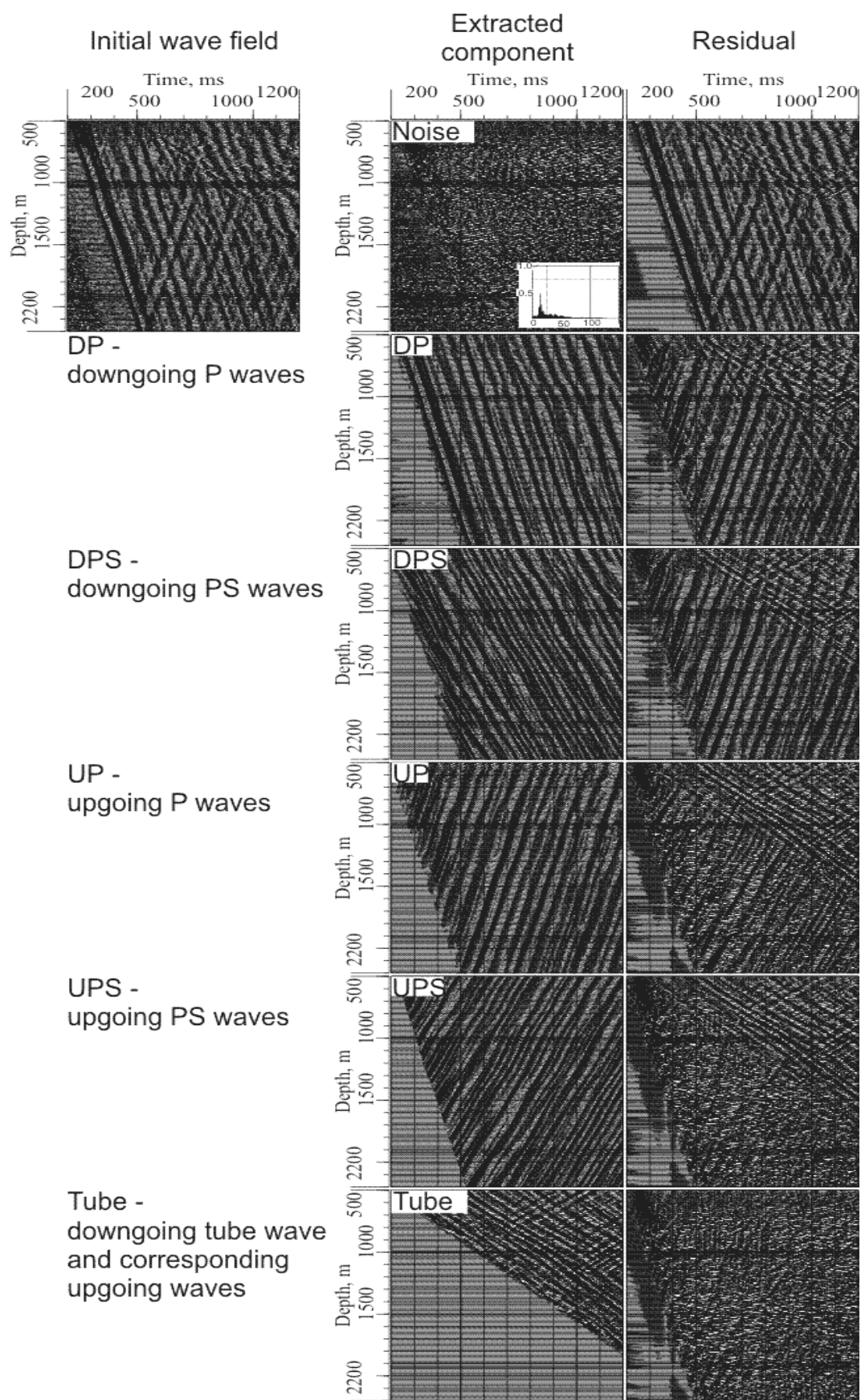upgoing waves

Noise

DP

DPS

UP
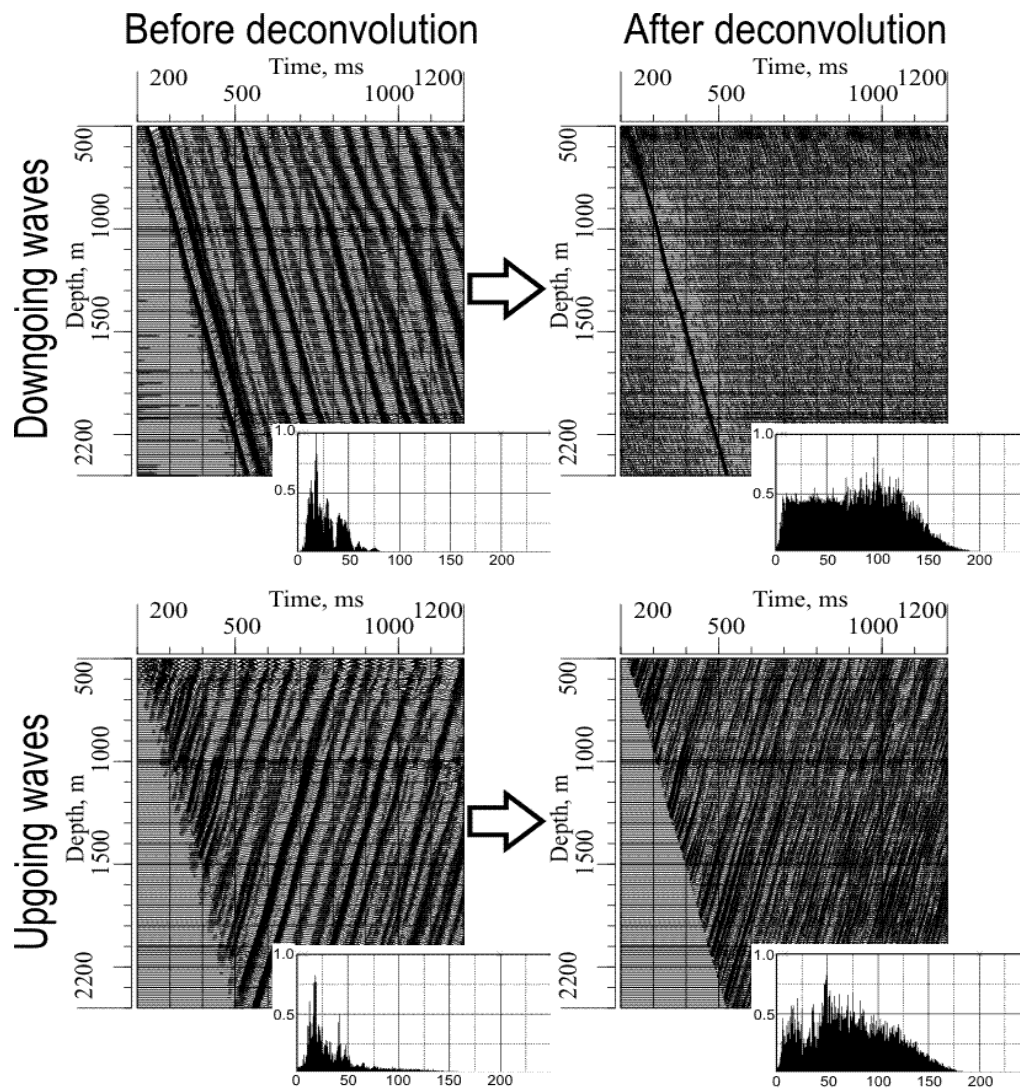
UPS

Tube

Fig.2. Additive wave field decomposition.

Fig. 3. Zero-phase deconvolution of VSP data.

case when intensive converted shear waves are observed, vector inversion algorithm should be implemented (Tabakov et al., 2005). This algorithm processes three-component reflection/ convertion traces of three wave types: monotype reflected (PP), converted reflected (PS) and downgoing converted (PS) waves. In the result of vector inversion we get values of reflection coefficients for PP and SS waves corresponding to the normal incidence.

Fig. 4 presents the acoustic impedance recovered from VSP data in comparison with log data. Such a perfect match as can be observed on the given figure confirms the accuracy of the velocity model estimated by VSP and hence ensures the reliability of the tie between surface seismic data and lithological section in the borehole.

Very important result that should be obtained at the end of VSP data processing is surface seismics tie to VSP data. Besides using the accurate velocity model for time-depth transformation this allows to increase the surface seismic resolution by performing extra deconvolution. The deconvolution operator is build to make surface seismic signal shape equal to that of processed VSP data (fig.4).

For far-offset VSPs migration procedures are performed to construct seismic image of the near-borehole area. If different wave types are used to get images they may be stacked into one seismic image. This firstly requires images' transformation into one physical parameter, for example, reflection coefficient of monotype P-wave (Reshetnikov et al., 2004). However, it's also possible to perform vector migration of full wavefield that can be done
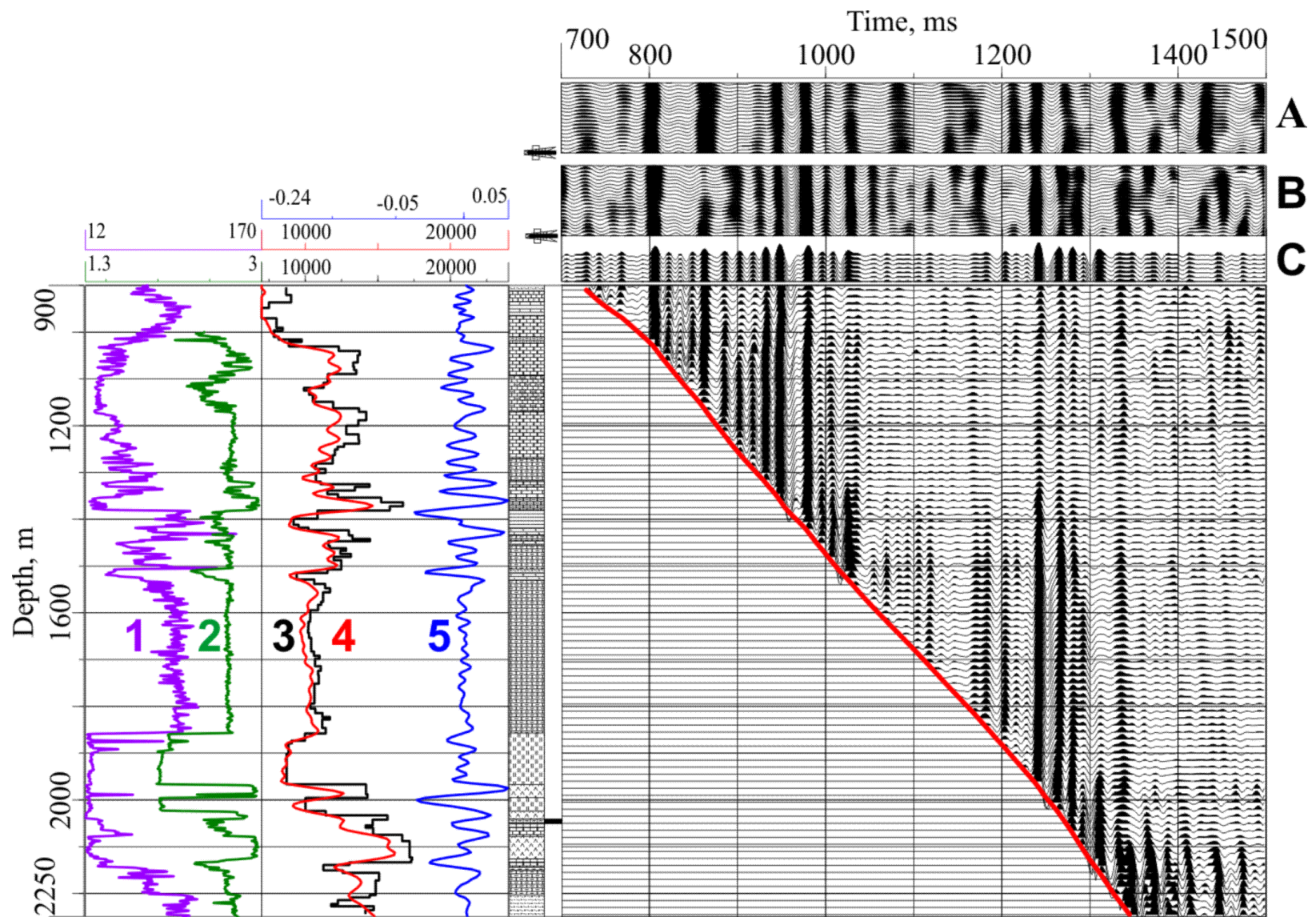
Fig. 4. VSP field tie to log data and surface seismics: 1 – acoustic log, 2 – gamma ray log, 3 – acoustic impedance derived from log data, 4– acoustic impedance derived from VSP data, 5 – primary reflection trace (in depth scale); A – a CDP section fragment, B – the same CDP section fragment after deconvolution by VSP trace, C – primary reflection trace (in time scale).

in three steps: extrapolation of the full wavefield from the receiving points into inner points of the media, decomposition of the extrapolated wavefield, vector inversion and getting reflection coefficient values (for the normal incidence) in all points of the media. This migration algorithm integrates information from all main wave types in the media. Amplidudes of such seismic image are directly corresponded to acoustic impeadance drop in the direction of outward normal to a surface. Implementation of vector migration prooved it to be much more reliable and accurate imaging than common scalar migration (fig.5).

CONCLUSIONS

To improve quality of VSP data processing it is recommended to use model-based processing, to keep additivity of wave field separation and perform several iterations to adjust and refine target wave parameters. It's also important to apply spike decomposition aiming at maximum possible spectrum extension (having a given signal to noise ratio). Application of the established principles provides high quality results of VSP data processing.

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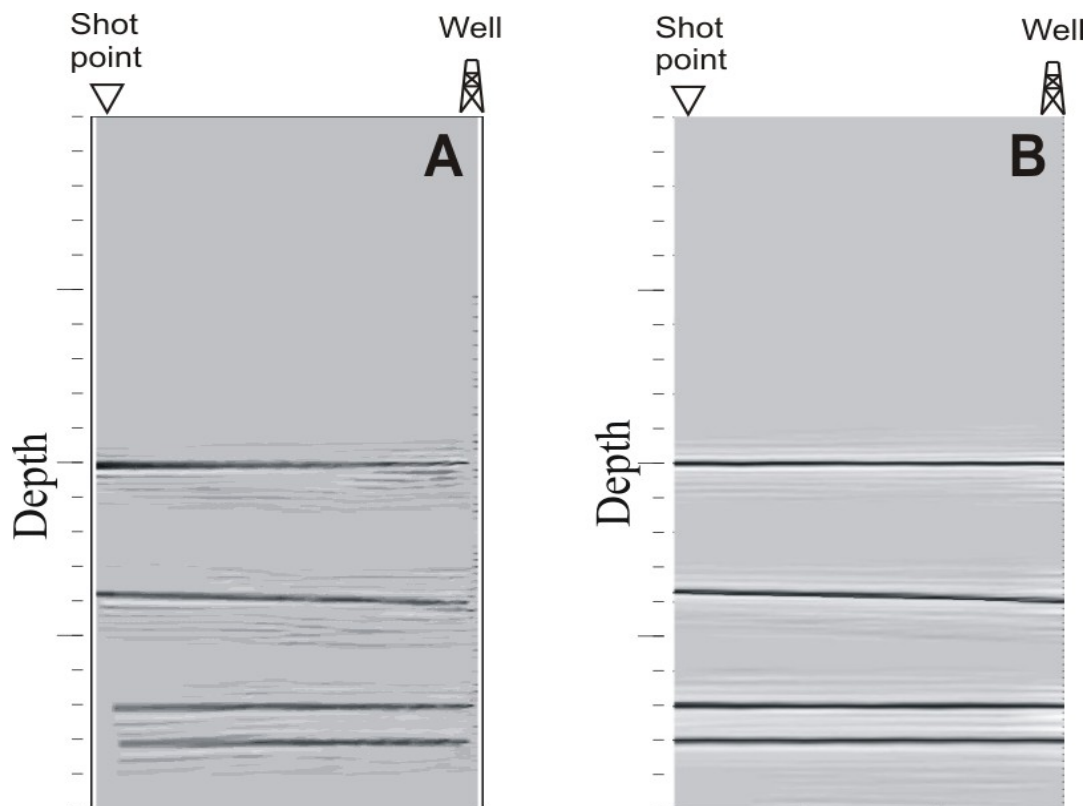
Fig. 5. A – seismic image obtained by Kirchhoff migration of synthetic data; B – seismic image obtained by vector migration of the same synthetic data.