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NEW APPROACHES IN HIGH-RESOLUTION SHALLOW SEISMIC PROSPECTION

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ABSTRACT

This dissertation deals with two aspects of the high-resolution near-surface seismic prospection. The first one is the high-resolution 3D seismic prospection, where a new approach based on a layered-earth model is presented. The second one is the problematics of S-wave identification on the near-surface records and consequent interpretation with the help of the S-waves. A new method of S-wave extraction is developed and advantages of joint P- and S-wave interpretation are demonstrated.

KEYWORDS: seismic refraction, high-resolution, 3D seismic prospection, S-waves, joint P- and S-wave interpretation

STRUCTURE OF THE THESIS

The dissertation is divided into five chapters (besides the Foreword and Conclusions chapters) dealing with particular aspects of the problematics:

1. Processing and interpretation of shallow seismic refraction data,
2. Comparison of the time-term method and tomography – a field example from the Děvín Castle,
3. Fracture detection with 3D seismic refraction – Ostaš Hill,
4. Determination of S-waves,
5. REFRACT3D – computer program for 3D refraction data processing.

The first chapter describes selected methods of 2D and 3D seismic refraction data processing and presents author's modification of the time-term method. The second and third chapters then show application of these methods on a particular problems of high-resolution 3D seismic prospection.

The fourth chapter deals with problematics of filtering S-waves from the shallow seismic records and possibilities of joint interpretation of the P- and S-wave cross-sections in the shallow seismics.

The fifth chapter aims to be the user manual for the REFRACT3D computer program. The REFRACT3D program is implementation of the author's modification of the time-term method.

PROCESSING AND INTERPRETATION OF SHALLOW SEISMIC REFRACTION DATA

This chapter is dedicated to selected methods of 2D and 3D seismic refraction data processing used further in the text for data interpretation. It begins with the 2D techniques for profile data processing – the plus-minus method and generalised reciprocal method. Then the seismic tomography, currently probably the most common data processing method, is discussed.

The main drawbacks of the seismic tomography for the high-resolution seismic processing are described. These are the smoothing during the inversion process and often also the gradient model of the subsurface, which is commonly used.

The smoothing becomes a serious problem when the smallest possible detailes are to be resolved which is, for example, the case of an archaeological prospection. The smoothing is inevitable for solving the non-linear inversion problem of the tomography and can not be avoided. Most of the tomography codes deals with this problem using the user-specified smoothing strength which can be specified according to the nature of the particular problem. However, even the low values of the smoothing may not be sufficient (as shown in the second chapter) and, moreover, the low values may also produce unstable results.

The gradient model used in the most of the tomography codes, even if it can describe most of

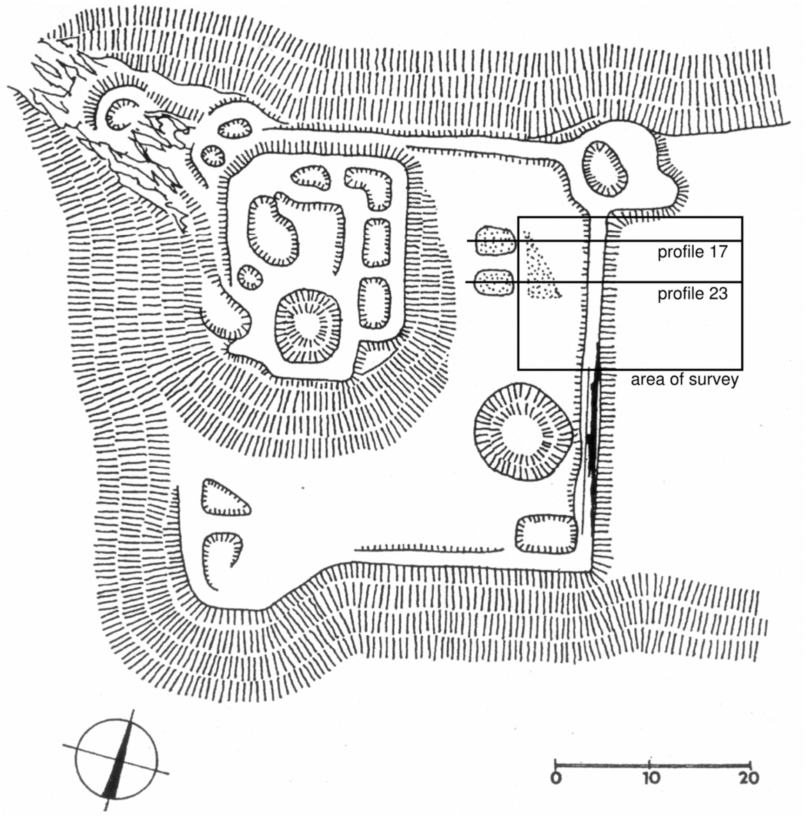


Fig. 1 A map of remnants of the Děvín Castle according to the archaeological prospection (Durdík, 1999). Plotted is the area of geophysical research – rectangular area of the 3D measurements and two seismic profiles.

the geological models, is not the best one when interpreting the position of layer boundaries. Moreover, the commonly searched objects in archaeological prospection (the remnants of walls and moats) are more easily identified from changes in depths of layer boundaries than from changes in velocities.

The author's solution for described problems is in modification of the time-term method, which is described in the last part of the first chapter. The original version of the time-term method was designed for a model of a layer over the constant-velocity half-space and it resolved the depth of the layer-half-space boundary and velocity of the half-space. It was easy to implement and computationally stable, however not adequate for the near-surface prospection, where abrupt changes in layer velocities are often encountered.

The modification of the time-term method divides the half-space boundary to a grid of small cells where the velocities can be considered constant (similarly as in the tomography). Size of these cells adequates to the step in sources and receivers. The small cells can well describe the sharp velocity contrast but increase the number of unknown parameters significantly. Thus the computation of results is not straightforward and is solved by introducing *a priory* information to stabilise solution in cells with poor ray-coverage.

The REFRACT3D computer program for data processing using the modified time-term method was written as a part of this dissertation.

COMPARISON OF THE TIME-TERM METHOD AND TOMOGRAPHY – A FIELD EXAMPLE FROM THE DĚVÍN CASTLE

The second chapter describes application of the modified time-term method in the field case of geophysical prospection on the Děvín Castle in Prague-Zlíchov (Fig. 1). The results of the time-term method are compared with results of the seismic tomography and of the plus-minus method (Fig. 2). The time-term method yielded much more detailed results than the tomography. Comparison of the time-term method's results with results of the plus-minus method showed, that even the subtle details resolved by the time-term method are likely to reflect the real changes in the geological media and are not computational artefacts. Interpreting obtained depths and velocities the entrance to the castle, remnants of walls and moat were discovered (Figs. 3, 4).

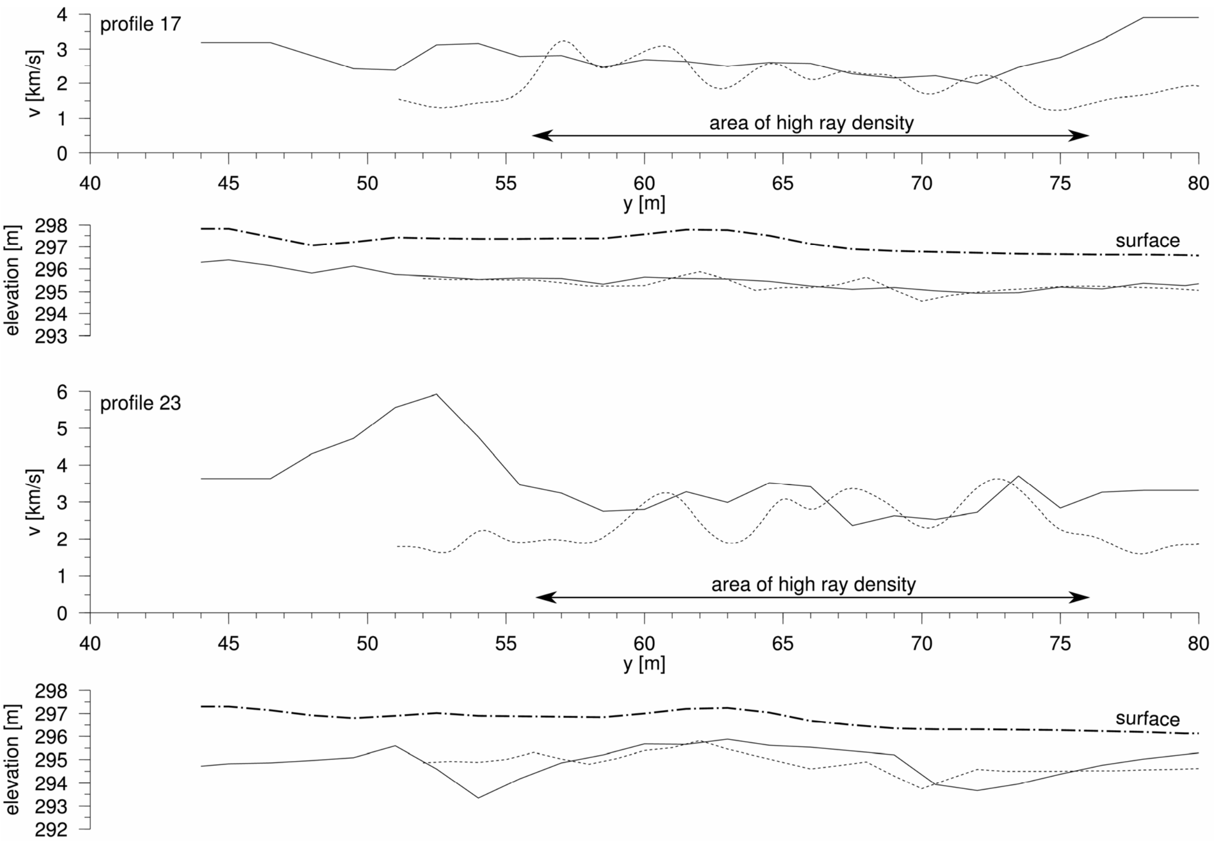


Fig. 2 A comparison between the results of the time-term and plus-minus methods. The results of the plus-minus method are plotted in a solid line, time-term results in a broken line. A dotted line denotes the present surface. The plus-minus method was applied on a 2D measured profiles 17 and 23, the time-term method results are extracted from the gridded results of 3D survey. The depths have a good overall coincidence, the velocities coincide in the centre of the surveyed area, where the density of rays is the highest. It can be seen that the depth profiles from the time-term method are less smooth and may contain a higher number of details than the depth profiles from the plus-minus method. The high velocities around the y-coordinate 52 on profile 23 at results from the plus-minus method are most likely caused by an error.

FRACTURE DETECTION WITH 3D SEISMIC REFRACTION – OSTAŠ HILL

The third chapter deals with problematics of determination of directions of fracture zones in the geological media. Currently most of the seismological techniques for determination of strike of fractures uses azimuthal variations of velocities – velocity anisotropy (or effects connected with the anisotropy – for example the shear wave splitting). The measurements in the field are usually carried out as a measurements along a set of profiles with different directions.

The author's proposal to this problematics (in connection with the 3D measurements described in detail in previous chapters) is to utilise the 3D measurements for this purpose. The weakened fractured zones should reveal themselves as a low velocity zones. The results from the test locality at the Ostaš Hill suggest, that the high-resolution 3D seismic tomography is also capable to resolve the orientation of fracture systems, even if two overlapping fracture systems are involved (Fig. 5).

DETERMINATION OF S-WAVES

The fourth chapter is devoted to identification of S-waves on shallow seismics records. The determination of the S-waves in shallow seismic represents a serious problem, which has not been satisfactorily solved yet and thus prevents the measurements and interpretation of S-waves from being used in the routine prospection. The main problem of S-waves usage in the shallow seismic prospection is in very small time separation between individual wave types on the seismograms and hence in impossibility to assign parts of the record to individual waves.

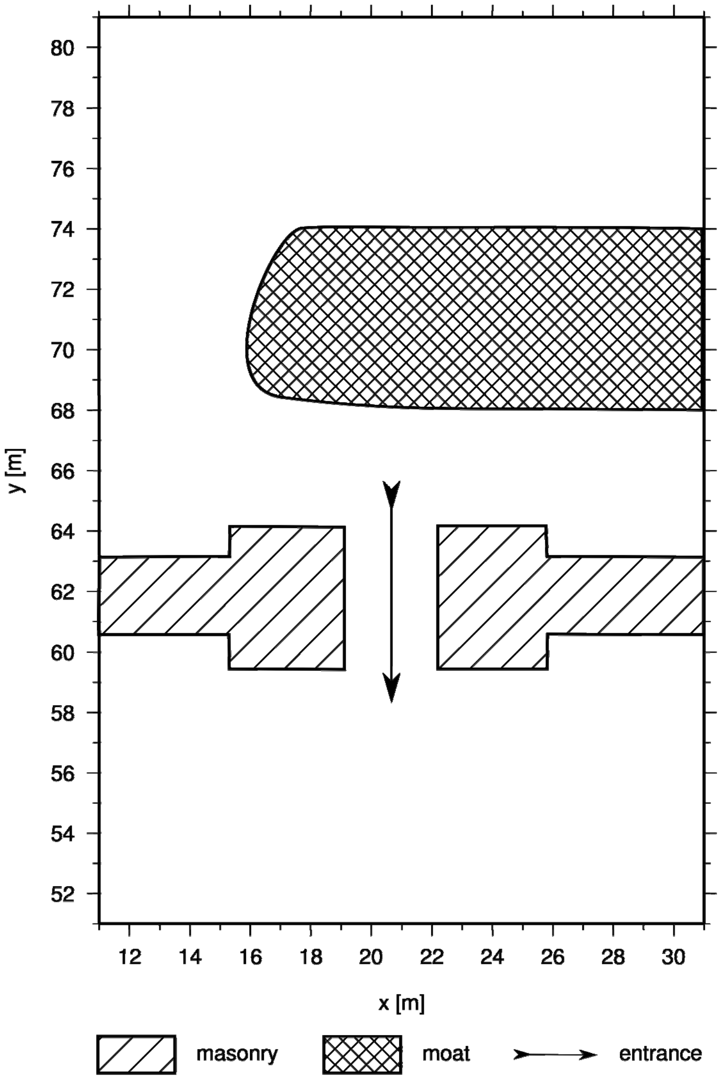


Fig. 3 The interpreted ground-plan of the entrance to the castle Děvín based on all applied seismic methods.

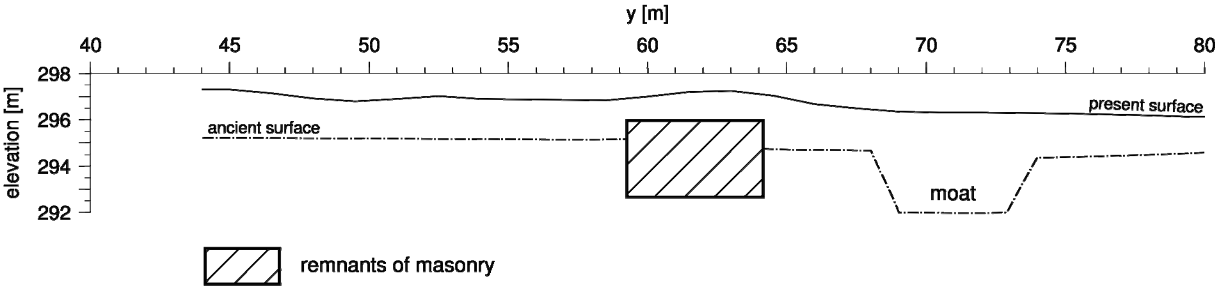
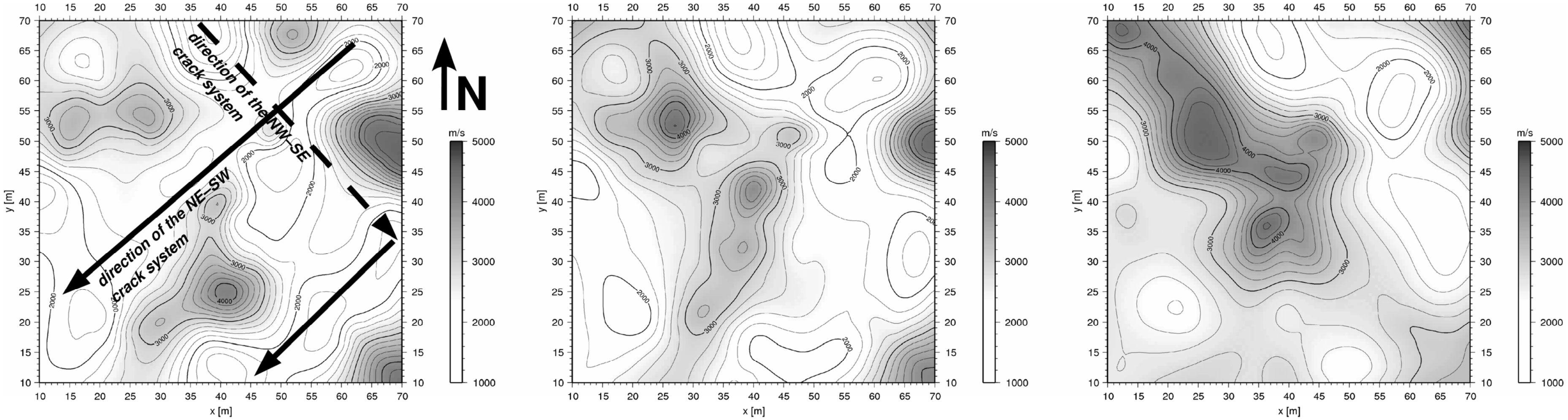
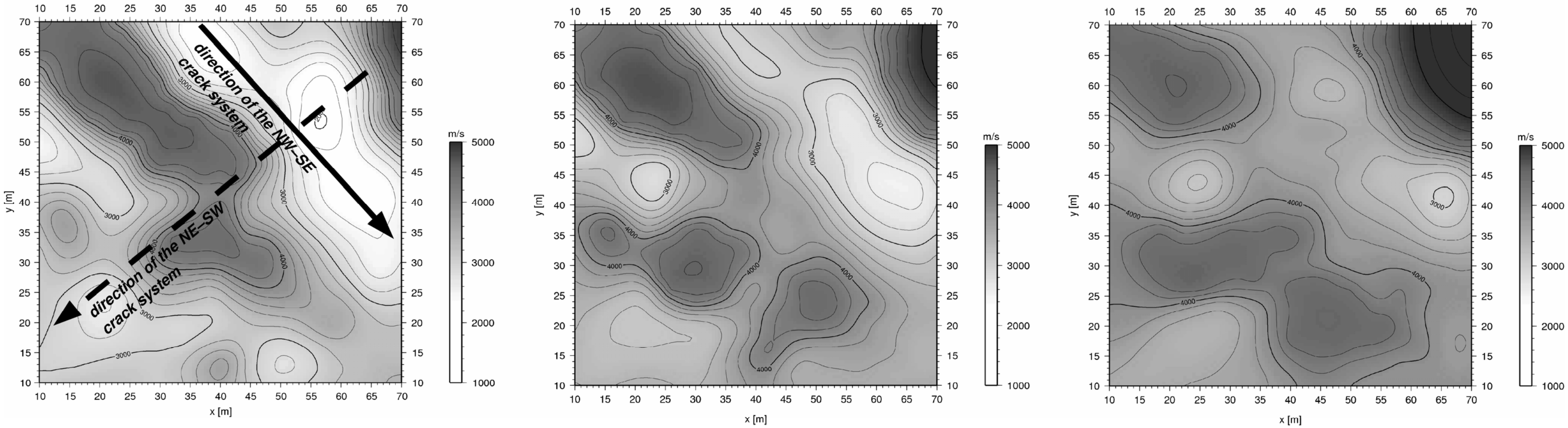


Fig. 4 The interpreted cross-section along profile 23 based on all applied seismic methods. Plotted is the thickened base of a rampart at the side of the gate, a three metres deep moat and a possible surface from the time, when the castle was built. Note the small terrain elevation (about one metre) where the castle was built. This elevation is further rising to the centre of the castle.



depth 5 metres **depth 7 metres** **depth 9 metres**



depth 11 metres **depth 13 metres** **depth 15 metres**

Fig. 5 Travel time tomography – weakened zones of individual fracture systems. Both fracture systems are subvertical. The NE–SW fracture system is considerable only near the surface. But it has a low depth reach and significantly penetrates only to a depth of 7–9 metres. The primary NW–SE fracture system penetrates deeper, at least to the depth of 15 metres, which is the effective depth of this survey.

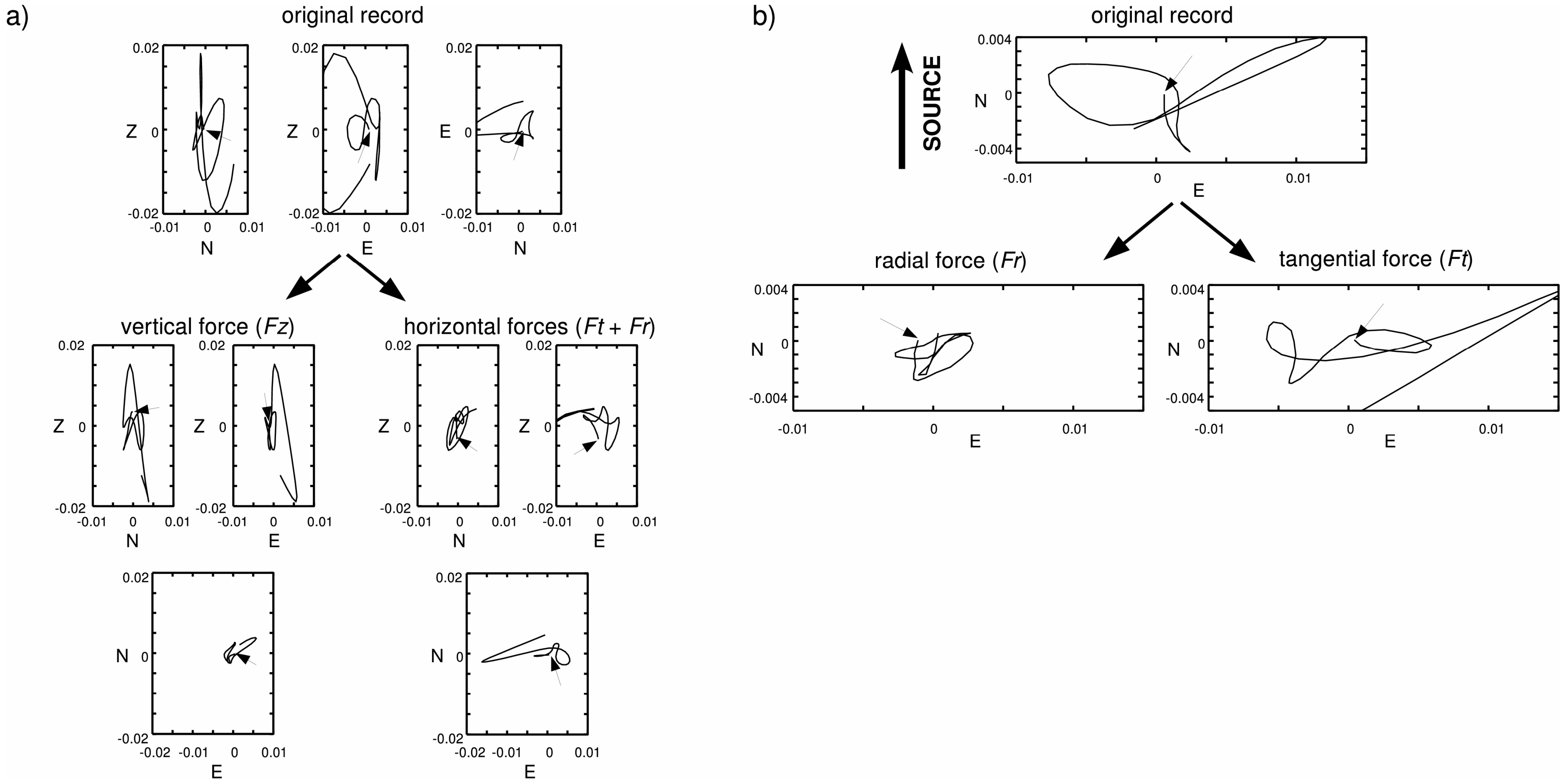


Fig. 6 Particle motion diagrams illustrating the decomposition of a seismogram to its components caused:
a) only by the vertical force (Fz) and by the horizontal forces (Fh, Fr). The N direction is oriented towards the source, thus parallel to the direction of the radial force Fr. The onset of the S wave is indicated by an arrow.
b) by the horizontal forces (Fh, Fr). The N direction is oriented towards the source, thus parallel to the direction of the radial force Fr. The separation to the Fr and Ft components is not absolute, but still significant. The onset of the S wave is indicated by an arrow. The data are from the locality Kobylisy.

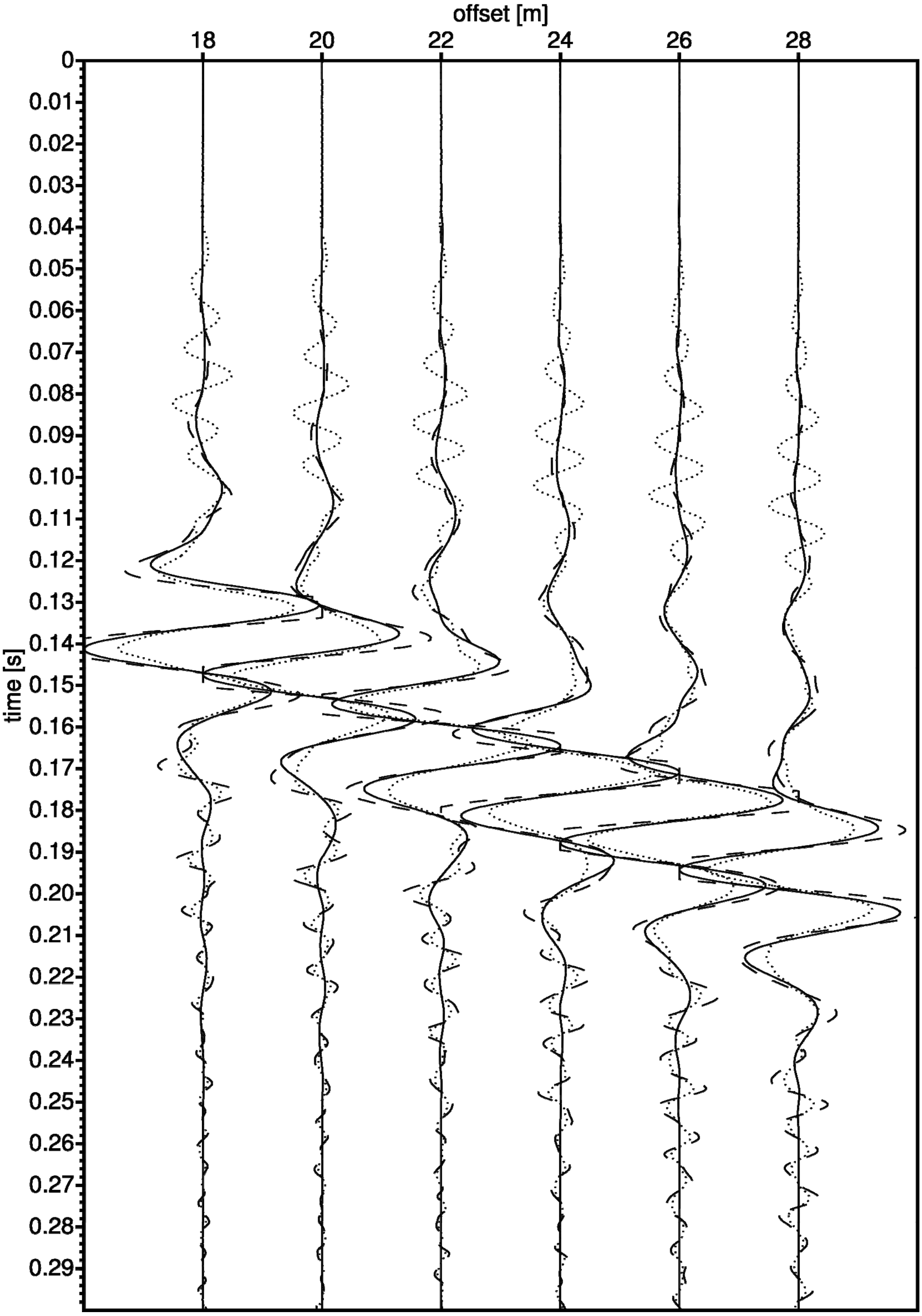


Fig. 7 Example of S-wave onsets filtering. A synthetic seismogram was computed for the two-layered media. The thickness of the upper layer was 2 metres, velocity of P-waves was 400 m/s and the P/S velocity ratio was 2. The velocity of the P-waves in the bottom layer(half space) was 1200 m/s and the P/S velocity ratio was 1.8. The synthetic seismogram is plotted in dotted line, a synthetic seismogram only for the S-wave is shown in dashed line. The filtered S-wave from the complete (dotted) seismogram is plotted in solid line. It can be seen, that the S-wave onsets are resolved very well. All traces are normalised to make all the features visible.

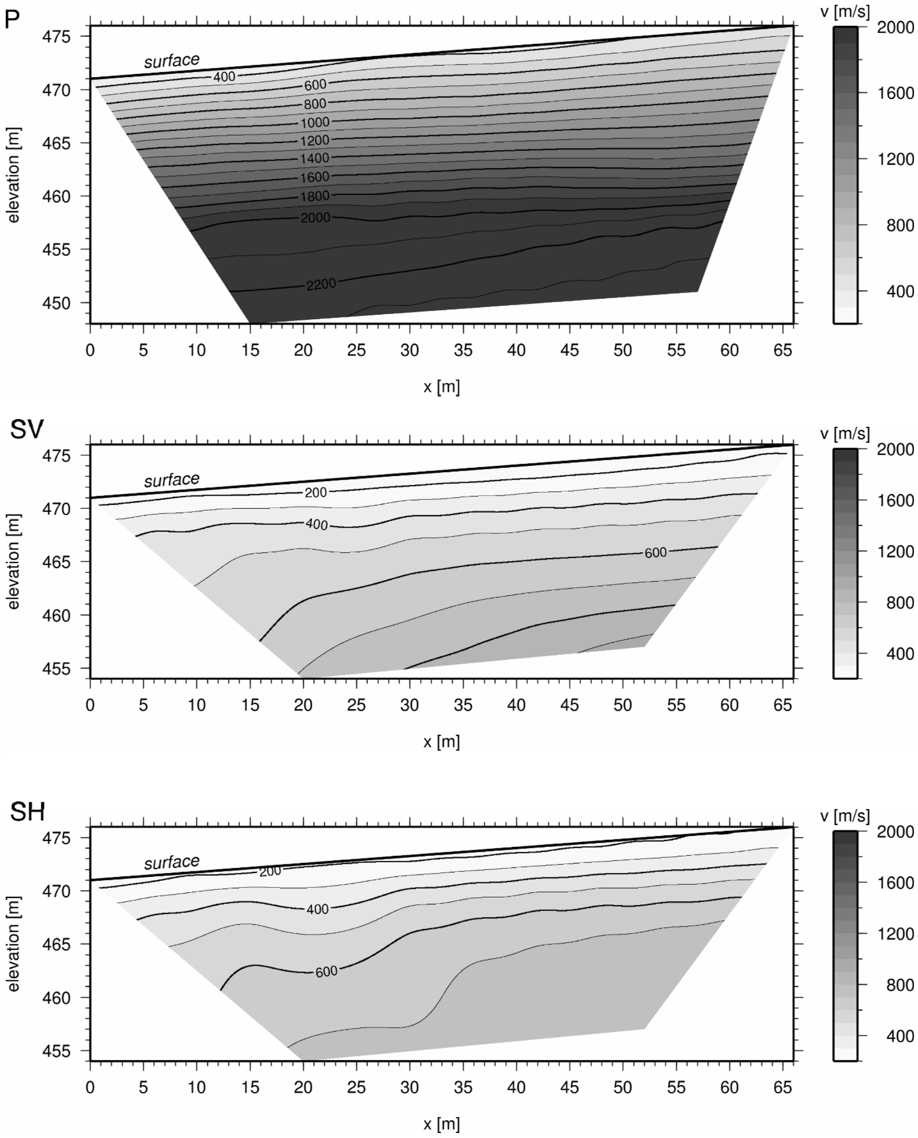


Fig. 8 Velocities of P, SV and SH waves from the travel time tomography. The onsets of SV and SH waves were determined using the GAS technique from records of P-wave source and horizontal components of geophones.

The problem of wave overlaps has been solved by number of different techniques either in the field by means of special sources or by numerous kinds of postprocessing in the office. An alternative to this approaches is the determination of S-wave profiles from the surface waves. However, the surface wave approach has also its own problems and is not considered in the thesis.

The first approach, the special sources, has many drawbacks as the sources are either clumsy (vibrators) or they produce only a low energy (horizontal strikes to a bar). However, the classical method of horizontal strikes to a bar is often used, when the prospection using S-waves is inevitable. This method is described in the thesis and is extended in such a way, that it enables also a distinction between the SV- and SH-waves which is necessary for anisotropy studies (Fig. 6).

The second approach, postprocessing, has certain advantages over the first one. For the field works reliable, cheap and powerful P-wave sources can be used (all of the commonly used P-wave sources generates also S-waves) and thus the works are fast and are not limited by weak sources. The drawback is, however, the demanding and time-consuming data processing. Numerous S-wave filtration techniques were developed in the „oil prospection“, however, according to the author's experiences, they can hardly be applied in the shallow seismic prospection. Thus a new method was developed, based on a comparison of neighbouring traces.

The neighbouring traces are shifted in time and summed. The wave types which are shifted to the same position are amplified while the others are weakened. This is similar to stacking in the common depth point method. However, the simple linear sum

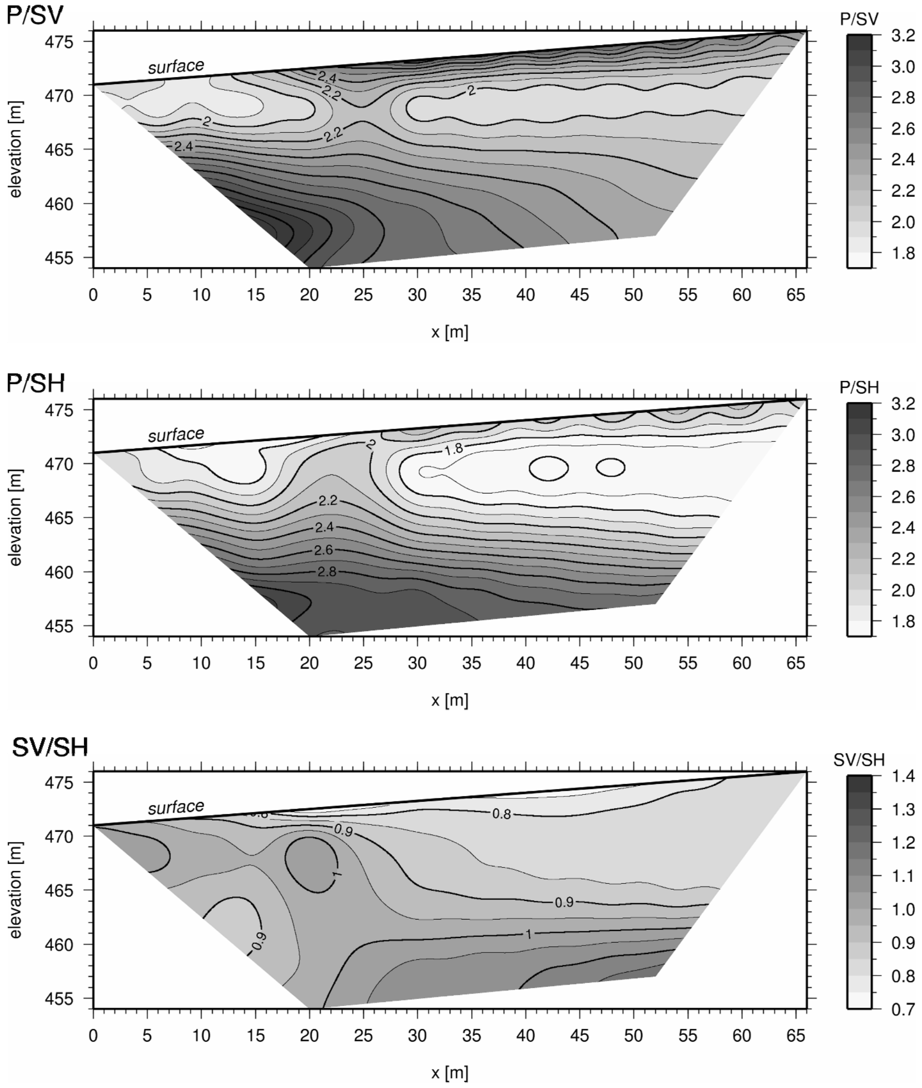


Fig. 9 Velocity ratios. The high values of the P/S velocity ratio might indicate groundwater. The water table is positioned to the highest P/S velocity gradient. The SV/SH ratio shows anisotropy of the S wave velocities and thus changes in physical properties of the rock massif. The SV-waves are faster in the bottom right part of the profile, while the SH-waves are faster in the upper right part. Hence, the change in lithology or in the angle of bedding can be expected. In this particular case, it is interpreted as a change in lithology from the Proterozoic chlorite-sericite phyllites (on the bottom) to the Carboniferous arkoses and conglomerates (on the top). The left part of the profile has no preferred anisotropy direction and is interpreted as a colluvial sediments.

can not be applied here, because it's filtration ability is weak, and the non-linear summation has to be used – GAS technique in this case (Málek et al., 2007). If the time shift is correct then the unwanted waves (P-waves) are filtered out and only the desired wave type (S-wave) is left on the seismogram (Fig. 7).

The wave-filtration method of S-wave separation is demonstrated on the synthetic seismograms and then on the real data from the locality Nečtiny. The field data from the three-component receivers are filtered to obtain P-, SH- and SV-waves and corresponding travel time curves. Next the individual velocity profiles were computed by means of the seismic tomography (Fig. 8). Finally, it is shown that even in the case, when individual velocity profiles do not allow satisfying interpretation, their combination can still lead to the detailed image of the subsurface (Figs. 9, 10).

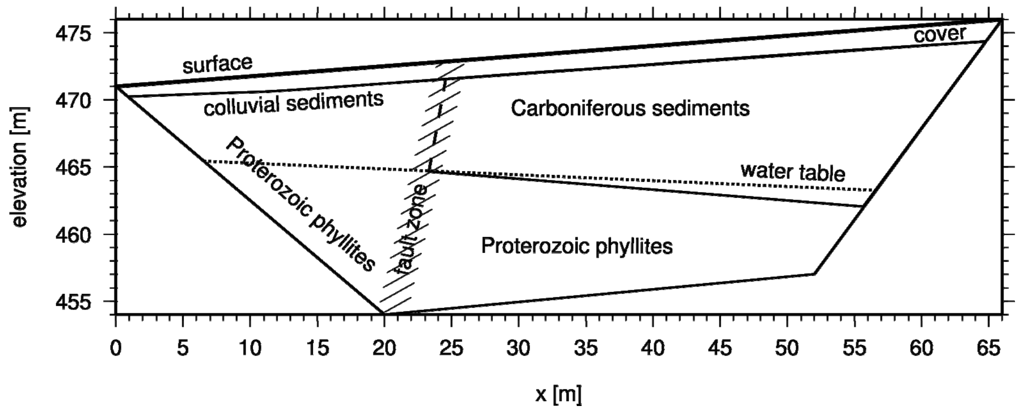


Fig. 10 Interpretation of cross-sections from Figures 8 and 9. This interpretation is based mostly on the P/S and SV/SH velocity ratios. The near surface soil and weathered layer is characterised by high P/S ratios. In this layer, the SH-waves are faster than the SV-waves. The groundwater table is placed into very steep gradient of P/S ratios. The phyllites and Carboniferous sediments are differentiated mainly according to their SV/SH ratios. The SV-waves are faster than the SH-waves in phyllites, while this ratio is reversed in the sediments. The zone with increased P/S velocity ratios inside the Proterozoic phyllites is interpreted as a fault zone. The zone with no preferred anisotropy on the left is interpreted as colluvial deposits.

CONCLUSIONS

The thesis presents two newly developed methods of seismic data processing – the modification of the time-term method and a new approach to S-wave extraction.

The 3D shallow seismic refraction is a method which is currently finding its way into the routine geophysical prospection but is not commonly used yet. Currently, most of the data processing is carried out via the seismic tomography technique. However, seismic tomography, as it has already been discussed, has also its limitations. Therefore the modified version of the time-term method was developed. As it was shown in this thesis, under certain circumstances (layered media) the new method leads to much more detailed image of the subsurface then the tomography.

The method of filtering S-waves according to their similarity on neighbouring records seems to be promising as it does not need any specialised source of S-waves. Therefore, the prospection is not limited by weak S-wave sources. Moreover, the interpretation based on both the P- and S-waves can be much more detailed then from the P-waves solely. These factors might help S-waves to enter the routine shallow seismic prospection. The drawback, however, is that the filtering is currently a laborious task. Hence the future development of this method should be concentrated on, at least partial, automation of this process.

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NOVÉ POSTUPY MĚLKÉ REFRAKČNÍ SEISMIKY

Jan Valenta

ABSTRAKT:

Práce se zabývá dvěma oblastmi mělké refrakční seimiky s vysokým rozlišením. První z nich je seismický 3D průzkum, kde je uveden nový postup zpracování dat založený na vrstevnatém modelu. Druhou oblastí je problematika měření pomocí S-vln. Byly vyvinuty dva umožňující extrakci S-vln a dále i jejich rozlišení na vlny SV a SH. Metodika je předvedena na terénních a datech a jsou ukázány výhody společné interpretace P- a S-vln.