JOURNAL OF BALKAN GEOPHYSICAL SOCIETY, Vol. 8, No.1, February, 2005, p. 20-27

Seismic Reflection Tomography: A Case Study of a Shallow Lake Survey in Lake Balaton

Pantelis M. Soupios[1], Tamas Toth[2]
(1) Department of Natural Resources and Environment, Technological Educational Institute of Crete, 3 Romanou, Chalepa, 73133, Tel.: +302821023037; Fax: +302821023003; E-mail: soupios@chania.teicrete.gr
(2) GEOMEGA Ltd, E-mail: info@geomega.hu

Abstract. *Shallow seismic reflection marine profiles were collected in the area of Balaton Lake in Hungary using high frequency boomer techniques, in order to get information about the stratigraphy of the sedimentary layers. The noise in these shallow marine seismic reflection data is analyzed, and a series of traditional seismic data processing techniques is applied to improve the S/N ratio and coherence. These are bandpass filtering, muting, spectrum analysis, gain, deconvolution and migration. The single fold of the survey did not allow velocity analysis to be done.*

Navigation control was derived from global positioning system. The shipboard GPS antenna positions were recorded for each shot at the time of trigger.

In addition, the geometry and the geophysical characteristics of the sediments are reconstructed by calculating the forward and inverse model. The inverse problem is solved by using the LSQR algorithm. In order to speed up convergence and stabilize the inversion several approaches are adopted, such as “damping” or “smoothing”.

INTRODUCTION

In petroleum industry, reflection seismics comprise the most widely used geophysical method for more than 60 years. However, until about 10 years ago, the shallow reflection method was not used to give petro-geological, hydrologic and geophysical information from the subsurface at depths less than 30 meters. Due to problems caused by the almost simultaneous arrival of different wave types, a limited number of papers have reported successful imaging at depths less than 20 meters (Birkelo et. al., 1987, Miller et. al., 1989). This is arises because of the small distance between the source and receivers.

In the present work, a seismic profiling technique and a digital acquisition system were used in the area of Balaton Lake in Hungary. A differential GPS antenna mounted on the catamaran located the common depth point positions of the seismic source/receiver units. The processed section revealed three distinct seismic reflections at the uppermost 10 m of the flood-plain alluvium.

Trapped gas can produce bright reflectivity in otherwise reflection free horizons and because of its very slow seismic velocity, delays the arrival of other subsequent reflected energy. Most of the known processing tools were applied, such as, bandpass filtering, mute (windowing), f-k filtering, spectrum analysis, gain, deconvolution and migration in order to get the best resolution in the final section.

Unfortunately, the record section suffers from the presence of multiple reflections, especially multiples of the sea bed reflection, which may obliterate primary reflection events in the later parts of the record. Multiples are always a particular problem when surveying in very shallow waters, since they occur at a short time interval after the primary events.

The single fold of the survey renders the velocity analysis impossible. In order to overcome this problem, a tomographic approach of the model was attempted, using reflection traveltimes from the predefined reflectors. Thus, the forward model was solved using finite-difference wave-equation modelling. Specifically, the ray tracing for the reflected waves is calculated using a fast finite difference scheme (Hole and Zelt, 1995). Raypaths and derivatives of travel-time with respect of the velocity field and the reflector are calculated using the approach of Williamson (1990) and Soupios et. al. (2004). The final velocity model is calculated using an algorithm based on a bidiagonalization of the system using Lanczos method (Lanczos, 1950), followed by a QR decomposition to find the solution.

This methodology is a simple but highly effective seismic surveying at sea that is widely used in a variety of offshore applications. It often provides good imaging of subsurface geology and permits estimates of reflector depth and geometry that are sufficiently accurate for many purposes.

SURVEY LOCATION AND LOCAL GEOLOGY

Lake Balaton is one of the most precious natural treasures of Hungary and is situated near Budapest. It is the largest lake of Central Europe, since its length is 77 kilometers and its width ranges from 4 to 14 kilometers (Figure 1).

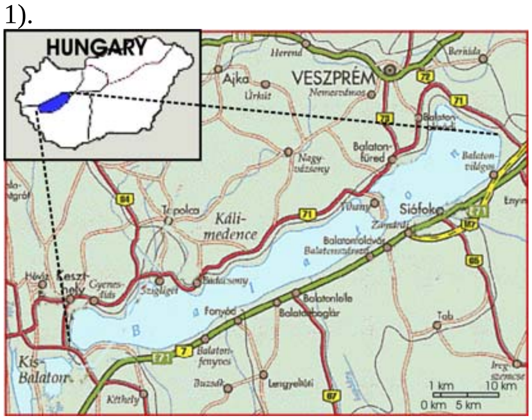

Figure 1.Location map of the broader study area.

The near surface material consists of unconsolidated, medium- to coarse-grained mud and medium to coarse gravel interspersed with thin discontinuous paleosols and clay. The near surface stratigraphy varies rapidly on the scale of meters. A test hole in the vicinity of the seismic section yields the following information: just below the water about 3.5-4 meters thick Holocene mud layer is present. The strata below the mud have an acoustic velocity around 1.7-1.9 km/s and density of a 2.0-2.3 gr/cm^3, which indicate stiff saturated clay (McLamore et. al., 1978).

FIELD PROCEDURES

The shallow marine reflection data were collected using the seismic profiling system –IKB-SEISTEC™ receiver with boomer source operating at 150 Joules and firing at 0.25 m intervals (Figure 2). A digital acquisition- PC based 50 kHz 16 bit sampling of filtered Seistec data recorded in SEGY format. The acquisition parameters are shown in Table 1.

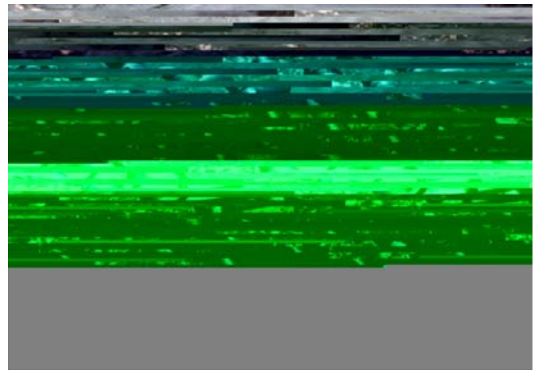

Figure 2. The seismic profiling system of SEISTEC™. The system include a receiver and a boomer source operating at 150 Joules.

Parameters	Measurement
Waveform format	SEG-Y, 2 bytes integer
Source	Boomer at 150 Joules
Firing interval	0.25 meters
Precision of positioning	< 1 meter
Num.of traces	512
Record length	1251 samples
Sample freq.	50 kHz
Length of profile	250 m
Num. of channels	1
Gain	Linear
Low cut filter	1 kHz, second order
High cut filter	10 kHz, second order

Table 1. Acquisition parameters in the survey

DATA ANALYSIS & PROCESSING

In marine seismic experiments, especially shallow marine seismic surveys, various surface-related noises are superimposed on the shallow reflections. These noises mainly include direct waves, guided waves that travel horizontally within the water layer and the layer beneath the water layer, reflected-refractions, water bottom multiples and side scattered noise (Lee, 1999).

Guided waves

Marine data are often contaminated by guided waves that travel horizontally within the water layer or in the layer beneath the water layer. These waves are dispersive, especially for shallow water depths; i.e., each frequency component travels at a different speed, which is called horizontal phase velocity (Yilmaz, 1987). Guided waves exhibit characteristics that depend on water depth and on the geometry and material properties of the substrata. Either a combination of deconvolution, gain, bandpass filtering and f-k filtering or simple spectral balancing is the most effective means of enhancing the amplitude and visibility of reflected signals relative to the guided waves (Buker et. al., 1998). Because of their prominently linear moveout in principle they also can be suppressed by dip filtering techniques (Yilmaz, 1987).

Multiples

The procedure which suggested in Table 2 is a good way to remove multiples of relatively long periods. This method, however, only works well to long-period water-bottom multiples and it removes useful subsurface reflections that have the same dip as the water bottom multiple reflections. In case where the water bottom and the underground layer is almost horizontal as well as for short-period water-bottom multiples, the procedures used to remove guided waves can also be used to suppress multiples.

Water bottom picking
Header statics (align water-bottom multiples)
Event Alignment
Apply fractional statics
Trace mixing
Remove header statics

Table 2. An effective flow to remove multiples

Side Scattered Noise

This noise commonly occurs at the water bottom where there is no flat and smooth topography. In our test site there exist no such conditions, i.e. irregularities which can act as point scatterers.

PROCESSING PROCEDURE – RESULTS

The main goal in processing reflection seismic data is to enhance primary reflections by suppressing unwanted energy in the form of coherent and random ambient noise. Data were processed on a SUN workstation using CWP/Seismic Unix (Cohen and Stockwell, 2001), free seismic processing package. The processing sequence is summarized in Table 3.

Processing Step	**Command**
Data conversion & read	SEG-Y → **segyread** → data in SU_format
Retrieve header information	**surange** (range of header values)
Fourier Spectrum of traces	**Suspecfx**
Window trace by key-word, or Mute traces above a defined polygone	**suwind**, sumute
Slope filter in f-k domain	**sudipfilt**
Sine-squared tapered filter	**sufilter**
Gain (tpow, gpow, qclip)	**sugain** (multiply data by t^{tpow}, take signed gpowth power of scaled data, clip by quantile on absolute values on trace)
Spreading correction	**sudivcor** (divergence correction)
Wiener predictive deconvolution	**supef**
Make and Transpose velocity matrix	**makevel**, **transp**
Migration	**sugazmig** (Jeno GAZDAG's phase-shift migration for zero-offset data)

Table 3. Processing procedure

The raw data as they have been acquired in Balaton Lake are shown in Figure 3. Three distinct clear reflectors are present. Further, the response of a trapped gas bubble is clearly shown at about the position of trace 430.

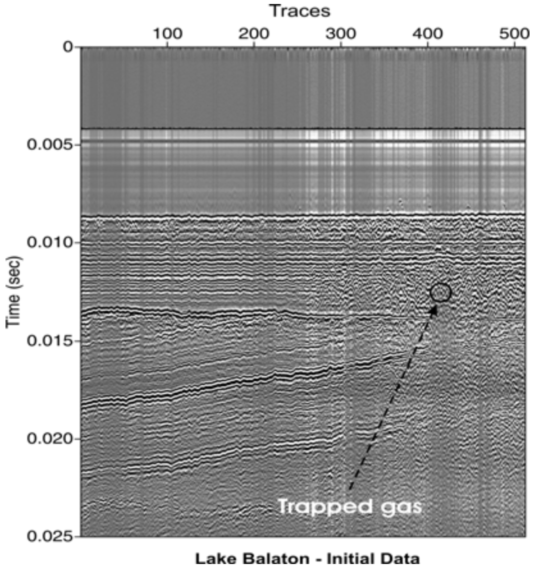

Figure 3. Raw zero offset section (512 traces with 25 cm trace spacing) containing 3 reflectors.

Since, the actual time zero is at around 4.15 msec, which is indicated by the high amplitude event, the first 4.15 msec of the section were muted, as shown in Figure 4.

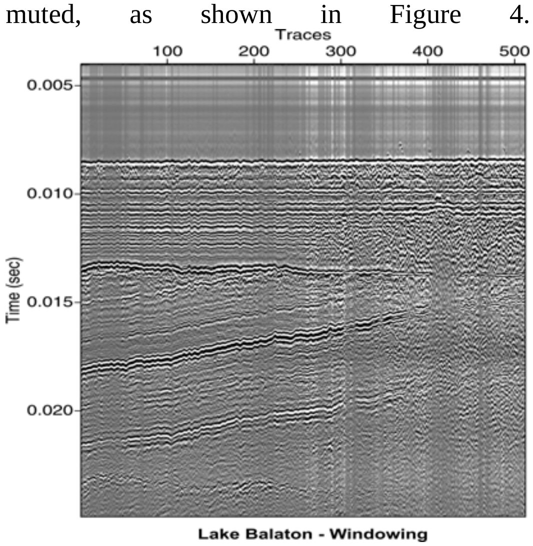

Figure 4. The first 4.15 ms of the seismic section is muted. The response of a trapped gas bubble is clearly shown at about the position of trace 430.

The spectrum of the data is presented in Figure 5 and shows peaks at frequencies 5 kHz and 7.5 kHz. It was desirable to filter the data before deconvolution.

.

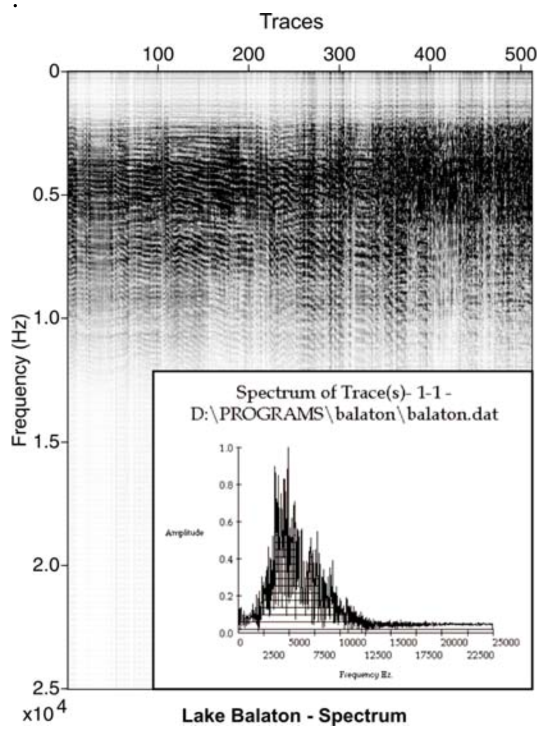

Figure 5. Amplitude spectrum of the seismic section. Most of the energy is included within the frequencies from 5 kHz to 7.5 kHz.

Since dipping events in the (t,x) space can be separated in the (f,k) space by their dips, we applied f-k dip filtering in order to eliminate certain types of unwanted energy from our dataset. In particular, coherent linear noise, such as guided waves, ground roll and side-scattered energy, are isolated from the reflection energy in the (f,k) space (Yilmaz, 1987). Additionally, we filtered the data with a wide band-pass filter. The filtered section is presented in Figure 6. A gain recovery function is also applied to the waveforms in order to correct the filtered data for the amplitude effects of wavefront due to spherical divergence and attenuation. The filtered-gained seismic section is presented in Figure 7. It is clear that some of the deeper reflectors are resolved quite well. The last step of processing procedure before attempting migration is deconvolution.

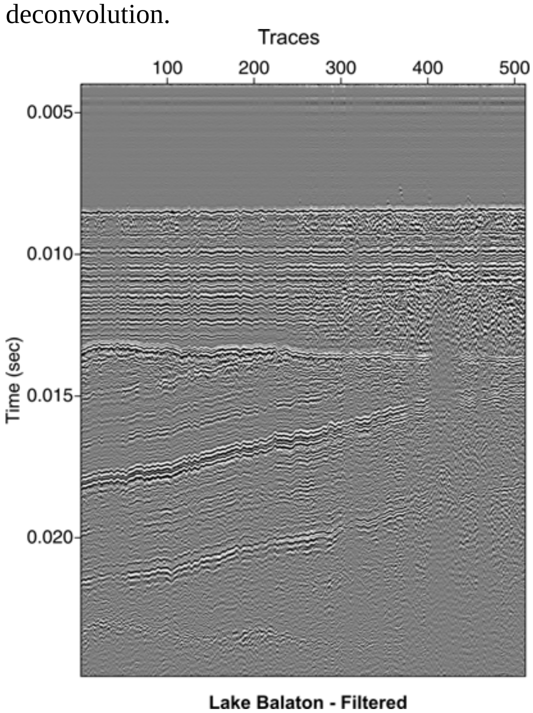

Figure 6. A band-pass filtered version of field record (Fig. 1). Note that the larger reflection amplitudes are confined to shallower times.

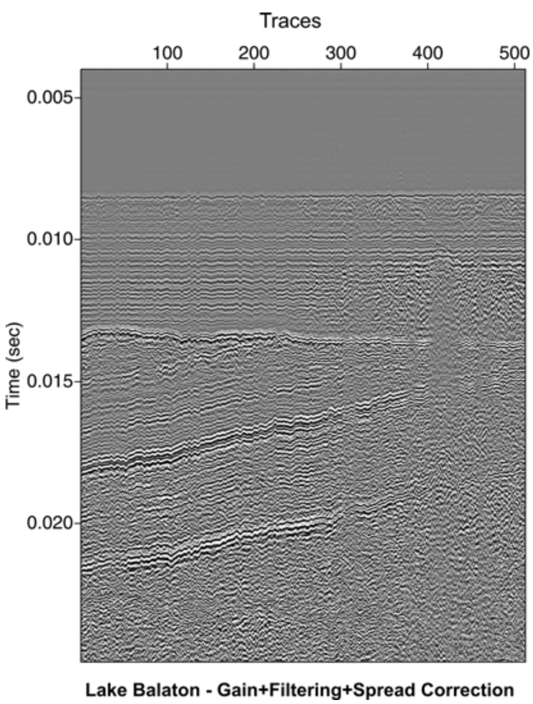

Figure 7. The same field section as in Figure 6 after correcting for geometric spreading and absorption losses. Deeper reflections are restored quite well.

Usually, prestack deconvolution is aimed to improve temporal resolution by compressing the effective source wavelet contained in the seismic trace to a spike. In the present work, an optimum Wiener predictive deconvolution (Robinson and Treitel, 1980) is applied and the result is presented in Figure8.

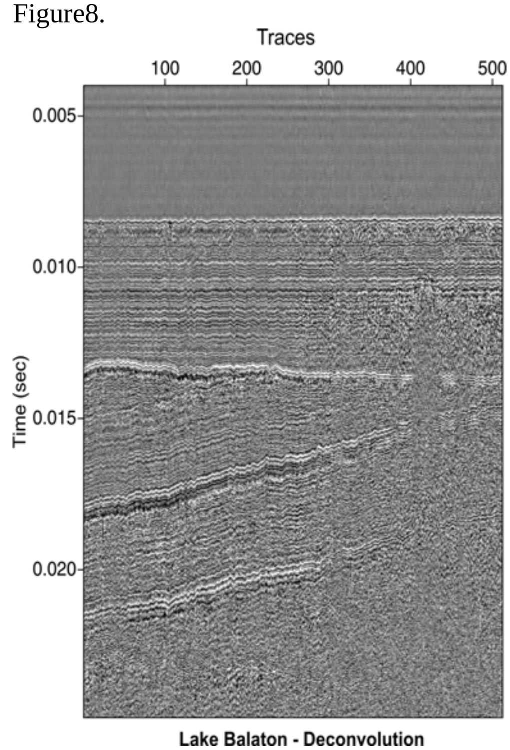

Figure 8. A deconvolution operator is applied to the data. This process compressed the source wavelet in the seismic trace to a spike.

Finally, the processed section is migrated applying the Jeno's GAZDAG phase shift migration for zero-offset data (Gazdag et. al., 1984). The migrated section is presented in Figure 9. In order to show the effect of migration in the initial filtered section, we superimposed the filtered and final migrated section. The result in shown in Figure 10.

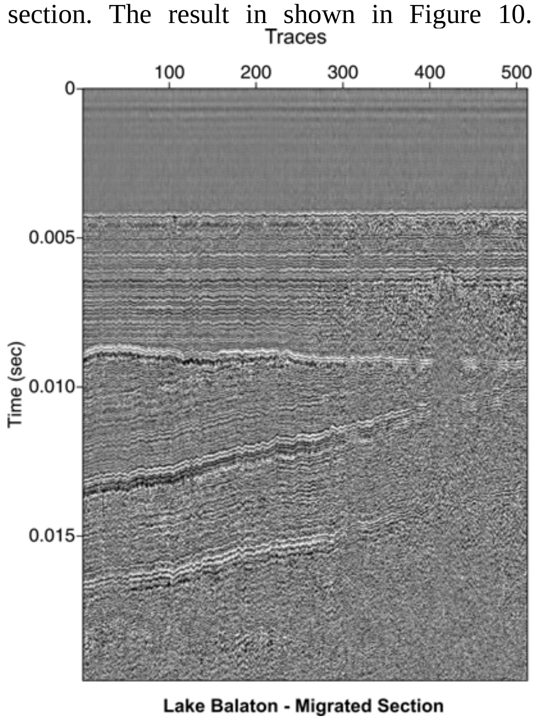

Figure 9. Phase shift migration of zero-offset data based on the work of Gazdag, et. al., 1984.

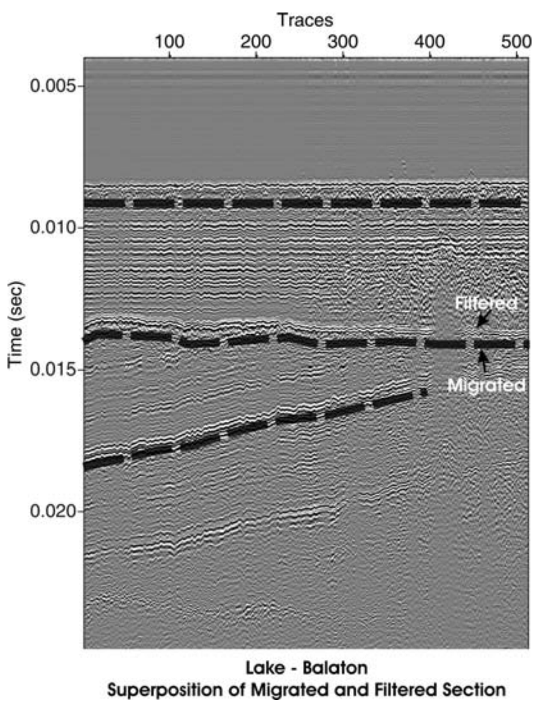

Figure 10. Superposition of the final migrated section on to the filtered section as presented in Figure 6. The thick black dashed lines show the reflector geometry after migration. It is clear that migration moved the reflectors to their true subsurface positions.

TOMOGRAPHIC APPROACH

In the past two decades, many works has emphasized the importance of the determination of the earth's velocity structure using seismic travel times. Not only the velocity structures, but also both velocity structures and depths to the interfaces are jointly inverted. Recently, much attention has been paid to reflection tomography. The basic idea of reflection tomography is to determine the subsurface velocity structure and reflector locations. However, because of the trade-off between media velocity and reflector depth (Tieman, 1994), the reflector interface and velocity cannot be uniquely determined without a priori information (velocity model or reflector geometry).

Based on the information's which are given above, we decided to approach the problem from the tomographic point of view. Thus, we inverted reflections traveltimes as they were picked from the distinct three reflectors of the previous reflection data analysis. In our work, we used a 5-layer, 1D background velocity model which was extracted from the borehole in the vicinity of the seismic section. Thus, we assumed the velocity model as is shown in Table 4.

Depth (m)	Velocity (m/s)
0.	1500.
3.	1600.
7.	1650.
11.	1800.
17.	1850.

Table 4. 1D initial velocity model

Since the reflection tomography provides better control on the configuration of the reflecting interfaces, we mainly invert for reflector geometries.

Ray Tracing

The reflection travel-times are determined by a finite-difference algorithm to compute travel-times in complex 3D velocity model and complex 3D reflector geometry (Hole and Zelt 1995). Snell's law for reflections is used in the vicinity of the reflecting interfaces. The raypaths and the depth derivatives are stored in order to construct the Jacobian matrix. A continuous reflector is also used and represented by a series of support points which depths vary as a function of horizontal offsets. Rays are traced backward in time from receiver locations down to reflecting interfaces, and then back to the source locations to determine the expected reflection travel-times (forward modeling).

Inversion

The inverse problem could be solved by either the Levenberg-Marquardt method (Levenberg, 1944; Marquardt, 1963), using both a damping factor and a roughness term, in the form of a second derivative smoothing filter to the slowness model (Constable et al., 1987), or by using the LSQR algorithm originally proposed by Paige and Saunders (1982). In the current work we present the results using the LSQR, since it is recommended for large, sparse linearized system of equations.

TOMOGRAPHIC RESULTS

In this section we present a tomogram as produced from the inversion of reflection traveltimes for each reflector. 512 source – receiver couples, resulting in 512 rays and 125 unknown variables for reflector reconstruction, were used. The receivers were placed on the surface and the sources were sunken 30 cm deep in the water. We also used a dense grid where we had 125 nodes in the x direction, 1 in the y direction and 10 in the z direction (depth), resulting in a total of 1250 nodes. We used three initial reflectors as shown in Figure 11.

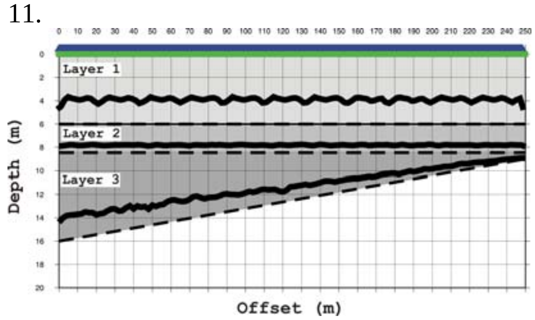

Figure 11. Reconstruction of reflectors, after inverting reflection travel times and applying appropriate regularization factors. The initial reflectors are described by the dashed black line and the continuous thick black line is the final inverted reflector geometry. The location of sources marked with squares and receivers marked with triangles.

For the interpretation of the first reflector it was necessary to scale the data in order to avoid round-off errors in the calculations. The final tomographic solution suggests a shallower reinstatement of the initial interfaces, in particular the first and second interfaces, as described by a flat reflector at the depths of 3.9 and 8 meters, respectively. The last reflector is a dipping interface with depths starting from 14 m (at the begging of the tomogram) to 9 m at the end of the tomogram. We should note that we traced the raypaths and we inverted for the reflectors applying the layer stripping method.

CONCLUSIONS

The present work shows the applicability of the inversion scheme as proposed by Soupios et. al. (2004), to a single channel data for near surface investigations. The inversion scheme adapted seems to produce reliable and accurate results. The conventional processing of reflection data produced interpretable time sections due to the pre-existing borehole data. However, the tomographic approach is capable to produce depth models even in the absence of borehole control and velocity analysis. The particular data set used falls in the last category. Therefore, an interpretation tool suitable for inverting data of near surface investigations is provided in these cases. On the other hand, tomographic solutions were not able to define and determine the biogenic gas bubbles present in Figure 3. This is due to the relatively large wavelength of the seismic source used. However, the single channel techniques are capable at least to locate the anomalous points.

ACKNOWLEDGEMENT

The authors acknowledge Prof. Antonios Vafidis, Prof. Gregory Tsokas, Prof. Berkan Ecevitoglu and Prof. Emin Demirbag for reviewing the paper and for their help to improve the current work. This work has been performed on behalf of the E.U. Cooperative geophysical techniques for surveying and quantifying potentially polluted sediments in European waterways (GEOWATERS). E.U. contract EVK1-CT-2001-30009 (www.geowaters.com).

REFERENCES

Birkelo, B., D.W., Steeples, R.D., Miller, M.A. Sophocleous, 1987, Seismic-reflection study of a shallow acquifer during pumping test, Ground Water, 25, 703-709.

Buker, F., Green A., and Horstmeyer H., 1998, Shallow seismic reflection study of a glaciated valley, Geophysics, 63, 1395-1407.

Cohen, J.K. and Stockwell, Jr. J. W., 2001, CWP/SU: Seismic Unix Release 35: a free package for seismic research and processing, Center for Wave Phenomena, Colorado School of Mines, www.cwp.mines.edu/cwpcodes.

Constable, S. C., Parker, R. L., and C. Constable, 1987, Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data: Geophysics, 52, 289-300.

Gazdag, J., and Sguazzero, P., 1984, Migration of seismic data by phase shift plus interpolation, Geophysics, 49 (2), 124-131.

Hole, J. A., and Zelt, B. C., 1995, 3-D finite-difference reflection travel-times, *Geophys. J. Int.*, 121, 427-434.

Lanczos, C., 1950, An iteration method for the solution of the eigenvalue problem of linear differential and integral operators, J. Res. Nat. Bur. Stand., 45, 255-82.

Lee, W. Myung, 1999, Processing of Single Channel Air ad Water Gun Data for Imaging an Impact Structure at the Chesapeake Bay, U.S. Geological Survey Bulletin 2169, U.S. Department of the Interior.

Research (CRAFT) Project entitled “Integrated

Levenberg, K., 1944, A method for the solution of certain nonlinear problems in least-squares: Quart. Appl. Math., Vol. 2, pp. 164-168.

Marquardt, D. W., 1963, An algorithm for least-squares estimation of nonlinear parameters: Soc. Industr. Appl. Math., J. Appl. Math., Vol. 11, pp. 431-441.

McLamore, V.R., Anderson, D.G., and Espana, C., 1978, Crosshole testing using explosive and mechanical energy sources, in Dynamic Geotechnical Testing ASTM STP 654: ASTM, 30-50.

Miller, R.D., D.W. Steeples, M. Brannan, 1989, Mapping a bedrock surface under dry alluvium with shallow seismic reflections, Geophysics, 54, 1528-1534.

Paige, C. C., and Saunders, M. A., 1982, LSQR: An algorithm for sparse linear equations and sparse least squares, A.C.M. Trans. Math. Software., 8, 43-71.

Robinson, E.A. and Treitel, S., 1980, Geophysical signal analysis, Prentice Hall, Inc., 468 p.

Soupios, P.M., Papazachos, C.B, Juhlin, C., Tsokas, G.N., 2001, Non-linear three dimensional travel-time inversion of crosshole data with an application in the area of middle Urals, Geophysics, 66, 627-636.

Soupios, P.M., Papazachos, Tsokas, G.N., Vafidis, A., 2004, Nonlinear Simultaneous Determination of Reflector Geometry and 3-D Velocity Structure, in review in Geophysical Prospecting.

Tieman, H. J., 1994, Investigating the velocity-depth ambiguity of reflection travel-times, *Geophysics*, 59, 1763-1773.

Williamson, P. R., 1990, Tomographic inversion in reflection seismology, *Geophys. J. Int.*, 100, 255-274.

Yilmaz, O., 1987, Seismic Data Processing, Soc. Expl. Geophys. S.E.G.