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Bootstrap inversion of local earthquake data in the Pannonian Basin

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Short-period waveforms of weak local earthquakes are inverted in order to retrieve the source mechanisms (moment tensors) for certain local events that occurred in the Pannonian Basin. Using the reflectivity method, synthetic Green's functions are computed for a given earth model for several hypocentral depths, and the moment tensor components are calculated by linear inversion. The shape of the source time function (STF) is also estimated. The moment tensor and event depth giving the best fit between the measured and synthetic seismograms are considered as the solution.

For the statistical validation of the results the bootstrapping technique is used. The estimated uncertainties in the resulting moment tensor components are plotted on the focal sphere in such a way that the significance of the double-couple, the compensated linear vector dipole, and the volumetric parts of the source can be assessed.

The moment tensor solutions for the selected events have an insignificant volumetric part, implying the tectonic nature of the events. The STFs are very simple, lasting 0.1–0.2 sec. The retrieved mechanisms are in agreement with the available clear readings of first-arrival *P*-wave polarities. The principal axes of the resulting source mechanisms also agree well with the main stress pattern published for the central part of the Pannonian Basin.

Keywords: earthquakes, waveform inversion, moment tensor, bootstrap resampling, Pannonian Basin

1. Introduction

Determination of mechanisms of weak local events is of prime interest while monitoring local seismicity, because these events reflect the stress pattern acting in the area under study and may help to map even its small-scale tectonic structure. Using analogue records, the only applicable method is to analyse the first motion polarities or, at most, the first amplitudes picked up from the seismograms. Such methods, which retrieve only a little information from the seismic records, often dominate digital data processing as well. However, digital instrumentation allows more advanced processing, aimed at earthquake source parameter retrieval, than

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the classical methods of first arrival analysis. Provided that a structural model of the given region is available, synthetic seismograms generated by various types of source can be constructed and compared with observed records in a suitable inversion scheme.

Several methods for point source mechanism retrieval with simultaneous determination of the source time function for teleseismic events have been developed. Techniques for inverting normal-mode data [BULAND, GILBERT 1976], surface waves [McCOWAN 1976, AKI, PATTON 1978, KANAMORI, GIVEN 1981], and body waves [DZIEWONSKI et al. 1981, LANGSTON 1981, SIPKIN 1982, OLDENBURG 1982] have been presented. Some of these approaches also allow the source depth to be determined. Sophisticated source retrieval methods also exist for inverting near-source strong motion recordings [JI et al. 2002, SEKIGUCHI et al. 2002]. These approaches make use of near-source data recorded by dense accelerometer arrays.

There is a gap between the teleseismic and near-source approaches which is not tackled satisfactorily. For regional and local earthquakes the seismic network is usually not dense enough and the knowledge of the medium is not detailed enough to allow the reconstruction of a finite-source model as in near-source studies. In comparison with teleseismic waveforms, seismograms of regional and local events contain much higher frequencies thereby making the application of teleseismic approaches dubious [KOCH 1991a,b]. The use of higher frequencies requires more detailed models of inhomogeneous media for which the synthetic seismograms, specifically the Green's functions, should be computed.

This requirement was followed by SILENY et al. [1992] and MAO et al. [1994], who used the method of modal summation to compute Green's functions in a vertically inhomogeneous medium of very fine structure. To improve the results, they used dynamic relocalization of the depths of the events, i.e. they used amplitudes to relocate event depths determined from the kinematics. Their method has been successfully applied for inverting weak volcanic earthquake data [PANZA, SARAO 2000, SARAO et al. 2001].

The central part of the Pannonian Basin (mostly occupied by Hungary) can be characterized by fairly low seismicity with local earthquake magnitudes of mostly less than 3. Weak events are usually recorded at only a few stations, so reliable focal mechanism solutions can only be obtained by waveform inversion. In this study waveforms of weak local earthquakes are inverted in order to retrieve the source mechanisms (moment tensors) and focal depths for certain events that occurred in the central part of Hungary. The method used slightly differs from that of SILENY et al. [1992] and it is capable of determining the uncertainties of the solution as well.

2. Theory

Central to any linear inversion of waveform data for the seismic source is the concept of the moment tensor. This representation was first proposed by GILBERT [1971] for studying the free oscillations of the earth. On using the moment tensor representation for body waves [AKI and RICHARDS 1980] one may write the *j*th component of the displacement field as

$$u_j(\mathbf{r},t)=\iint_S M_{kl}(\mathbf{r}',t)*G_{jk,l}(\mathbf{r},t;\mathbf{r}',0)\,\mathrm{d}S$$

where M_{kl} are the components of the moment density tensor, $G_{jk,l}$ are the elastodynamic Green's functions, **r** the position of the receiver, **r'** a point on the fault surface, and dS an element on the fault surface S. The symbol * denotes temporal convolution. When considering only wavelengths for which S is effectively a point source, the entire surface may be considered as a system of couples operating at a point. The moment tensor is then defined as

$$M_{kl}(t)=\iint_S M_{kl}(\mathbf{r}',t)\;\mathrm{d}S$$

and

$$u_j(\mathbf{r},t)=M_{kl}(t)*G_{jk,l}(\mathbf{r},t;\mathbf{R}_0,0)$$

where $\mathbf{R}_0$ is the centroid of S. In general, this equation contains terms in both M_{kl} and $\dot{M}_{kl}$ (where a superscript dot denotes the time derivative) [AKI and RICHARDS 1980]. However, in view of the distance dependence of these terms and the symmetry of $\dot{M}_{kl}$, the far-field displacement can be written as

$$u_j(\mathbf{r},t)=\sum_{k=1}^{6} m_k(t)*g_{jk}(\mathbf{r},t;\mathbf{R}_0,0)$$

where $\mathbf{m}(t)$ is the vector containing the six independent elements of the moment rate tensor, i.e.

$$m_1(t)=\dot{M}_{11}(t) \qquad m_4(t)=\dot{M}_{13}(t)$$
$$m_2(t)=\dot{M}_{12}(t) \qquad m_5(t)=\dot{M}_{23}(t)$$
$$m_3(t)=\dot{M}_{22}(t) \qquad m_6(t)=\dot{M}_{33}(t)$$

and the g_{jk} are the corresponding Green's functions. This is the linear relationship upon which most inversion schemes depend.

For weak events, when the focal mechanism is considered as constant in time during the rupture process, all of the $m_k(t)$ components have the same time dependence $s(t)$. Then the far-field displacement seismogram is

$$u_j(\mathbf{r},t)=\sum_{k=1}^{6} m_k \cdot \left[s(t) * g_{jk}(\mathbf{r},t;\mathbf{R}_0,0)\right] \qquad (1)$$

where **m** is the vector containing the six independent elements of the moment tensor (constants in time) and $s(t)$ is the source time function (STF).

3. The inversion procedure

According to Eq. (1) if the STF and the Green's functions (i.e. the velocity distribution and hypocentre coordinates) are known, the earthquake waveforms can be inverted for the unknown moment tensor elements by a linear procedure. However, the STF is usually unknown, and the velocity structure and hypocentre coordinates are only known with a degree of uncertainty. If, besides the moment tensor, all or some of these parameters are also treated as unknowns, the inversion problem becomes nonlinear.

In practice, routine event location techniques usually determine the epicentre coordinates acceptably well, while the hypocentre depth is usually poorly resolved. Since the Green's functions are very sensitive to the event depth, in the course of the moment tensor inversion procedure the event depth must be considered as unknown.

The velocity structure also has a strong effect on the Green's functions, so it, also should be treated as an unknown. However, the weak local events in the Pannonian Basin are usually recorded at only a few digital stations in view of which there are relatively few data. This fact simply does not allow us to increase the model space by the unknown velocity values and layer thicknesses. Moreover, variation of the velocity structure during the inversion process would require so much computer time to continuously re-compute the Green's functions that routine application of the waveform inversion would not be economical.

Based on the above discussion, in the course of the waveform inversion procedure used in this study we carried out the following steps:

1) We estimated the source time function from the *P* form recorded at the station nearest to the event.

2) Keeping the routinely calculated epicentre coordinates as fixed parameters, we calculated Green's functions by the reflectivity method for several hypocentre depths and for all stations that recorded the event under consideration. We used the reflectivity method because it allows the entire wavefield for one-dimensional (1-D) earth models to be calculated.

3) We solved Eq. (1) for all possible depth values by a least squares linear inversion method in order to estimate the moment tensor. The best depth and moment tensor are given by the case that produces the smallest sum of squared error between the recorded waveforms and the calculated seismograms. The truncated singular value decomposition (TSVD) algorithm is used here to solve Eq. (1) [see, e.g. AKI, RICHARDS 1980, VAN DER SLUIS, VAN DER VORST 1987, XU 1998].

4) If we know the moment tensor and the Green's functions, we can again solve Eq. (1) to refine the STF.

5) We repeated steps 3 and 4 until the event depth, the STF, and the moment tensor components did not change considerably. The F-test known from statistics helps one to decide when to stop the iteration.

4. Bootstrapping

In order to determine the reliability of the solution of an inversion procedure, one must evaluate the variance of the model parameters. In many cases the model parameters are a linear function of the data, and model variance can be estimated by mapping the data variance to model space. However, estimation of data variance is a problem in itself. Because many geophysical data are non-reproducible (e.g. a certain earthquake cannot be repeated), it is not possible to verify any assumptions made with respect to the probability distribution of the data. A further difficulty in estimating model variance is that for many problems the physical relationship between data and model is nonlinear. For these cases it is often not possible to find an analytical expression for model variance in terms of data variance.

As a means of overcoming the above mentioned difficulties it is recommended that the bootstrap resampling technique be used. This method is completely insensitive to the probability distribution of the data: the data do not have to follow a normal distribution and it is also not necessary that each item of data has equal variance. Furthermore, this technique allows evaluation of statistical properties that cannot be determined analytically. A short discussion of the mathematical basis of bootstrapping and its application to a geophysical inverse problem can be found in TICHELAAR, RUFF [1989].

A bootstrap resample is a random selection of n data out of n original data in such a way that any original item of data may be chosen more than once. This means that for an extreme case a particular resampled data set may consist of n identical observations of one of the original data items. If N bootstrapped data sets are created and all of them are inverted, we get N solutions for the model parameters. Then several statistical properties of the model parameters can be determined, such as standard deviation, mean, or median. It can also be very informative to plot the histograms of the estimated model parameters. The construction of confidence intervals is also possible.

The issue of what magnitude of N should be chosen to get a good estimate of the model variance is not settled yet. EFRON and TIBSHIRANI [1986] give rough estimates of N and show that $N \sim 100$ is a reasonable value for the bootstrap estimate of the standard deviation. However, in order to estimate confidence intervals a much larger N (O(1000)) is required. Because the bootstrap technique requires the full inverse problem to be solved N times, it is clear that the use of this method is computationally a very demanding job, particularly when confidence intervals are desired.

In our inversion problem the model space consists of the moment tensor elements, the event depth, and the STF. After all, the relation between them and the data (waveforms) is nonlinear. Moreover, it is very difficult to estimate data uncertainty and the errors introduced by the use of an inadequate velocity model. From the above discussions it follows that the bootstrap technique appears to be the only appropriate method for estimating model uncertainties.

5. Data

The waveform data used in this study were recorded by the three-component seismological stations of the Microseismic Observation Network of Paks (MONP), maintained by Georisk Ltd. in Hungary (*Fig. 1*). The transfer functions of the velocity instruments are flat above 1 Hz. To remove low- and high-frequency numerical effects from the records, a causal bandpass filter from 1 to 5 Hz was applied to the time series after transforming them to displacement. The same filter was applied to the displacement Green's functions. The synthetic seismograms were calculated with a sampling interval of 0.024 s. As the data were originally sampled at 125 Hz, they were resampled to match the sampling interval of the Green's functions.

For the three events studied (circles in Fig. 1) the network was azimuthally well distributed. Because of the small location uncertainties of 1–2 km, the epicentre coordinates were taken from the Hungarian Earth-

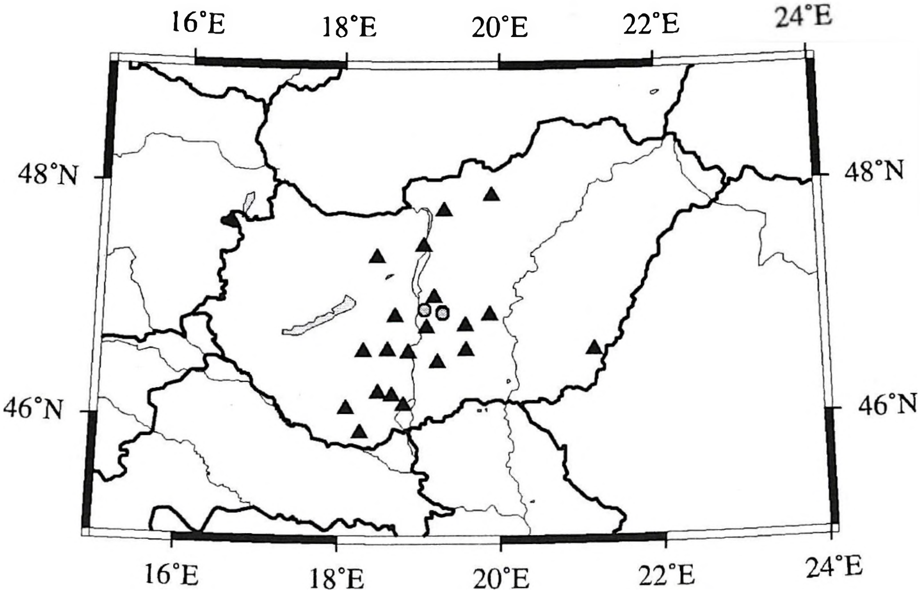

Fig. 1. Map showing the epicentres of the events (circles) selected for the present study together with the digitally equipped seismological stations. Two events occurred at practically the same epicentral coordinates

1. ábra. A jelen tanulmányban feldolgozott földrengések epicentrumai (körök) és a digitális szeizmológiai hálózat állomásai (háromszögek). Két esemény epicentruma gyakorlatilag megegyezik quake Bulletin [TÓTH et al. 1996, 1997, 2001]. However, hypocentre depths were considered as unknown parameters to be determined by the waveform inversion process.

For generating the Green's functions, the reflectivity method [MÜLLER 1985] was used, since this allows the entire wavefield for 1-D velocity models to be calculated. It is by no means easy to construct a suitably detailed velocity function required for inverting local waveform data. For this study we derived a rather simple velocity model from measured traveltimes of local earthquakes and controlled seismic sources (*Fig. 2*).

Since epicentral distances usually range from a few tens of kilometers to 100–200 km with a wide range of event–station azimuths, if one uses the same simple velocity structure for all event–station pairs it is almost

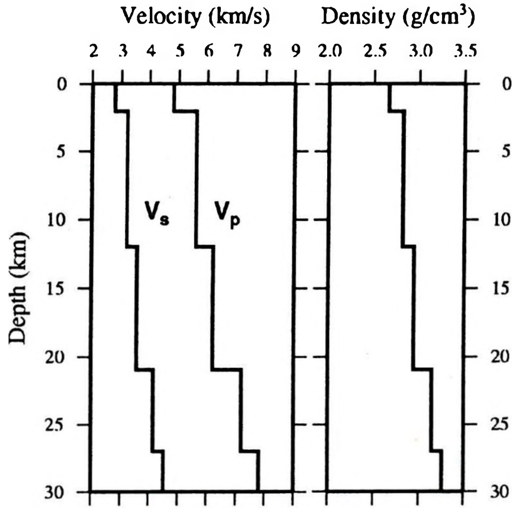

Fig. 2. 1-D earth model used for calculating Green's functions with the reflectivity method. The *P* velocities are deduced from measured traveltimes of local earthquakes and controlled seismic sources. The *S* velocity is assumed to follow v_P as $v_S = v_P/\sqrt{3}$. For density, another empirical law is used: $\rho = 1.7 + 0.2 v_P$. In this study the earth model is not varied during the inversion process

2. ábra. A szintetikus Green-függvények számításához használt 1-D földmodell. A *P* hullámsebességeket lokális földrengések és felszíni robbantások első beérkezési időadatainak felhasználásával határoztuk meg. Az *S* hullámsebességekről feltételeztük, hogy a $v_S = v_P/\sqrt{3}$ összefüggés szerint követik v_p-t. A sűrűség meghatározásához szintén egy empirikus összefüggést használtunk: $\rho = 1.7 + 0.2 v_P$. A földmodellt ismertnek tételeztük fel az inverzió során inevitable that inconsistencies will be introduced. The effects of inadequacies of the structural models were investigated by SILENY et al. [1992] and KRAVANJA et al. [1999]. They proved, by synthetic tests, that a poorly known velocity structure: (1) introduces apparent non-double-couple components in the moment tensor solutions; (2) contaminates particularly the CLVD, which may be as large as 40 per cent; (3) maintains the orientation of the double-couple within ±10°; and (4) leads to spurious peaks in the source time function [KRAVANJA et al. 1999].

An inadequate velocity structure is certainly not capable of predicting the reflected and converted waves arriving between the first *P*- and *S*-waves. So, in order to reduce the above-mentioned effects on the inversion results, only the first *P*- and/or *S*-waveforms were inverted. The use of *S*-waves in the inversion process may be crucial when the first *P*-arrival is too small in amplitude to trigger the instrument (i.e. it is absent from the seismogram) or its signal-to-noise ratio is too small. If one includes *S*-waves in the calculations it also helps to constrain the solution.

6. Iversion results

Displacement seismograms derived from the observed velocity recordings were used to invert for the seismic moment tensors and source time functions of three local earthquakes. The epicentres of the three events were close to each other in the central part of Hungary (Fig. 1). Only waveforms with a good signal-to-noise ratio were used in the inversion process.

The inversion results for the local event that occurred on June 9, 1995 near Szabadszállás are presented in *Fig. 3*. The map depicts the position of the epicentre and the seismological stations used in the calculations. To the left of the map the observed seismograms (bold lines) and the synthetic waveforms (thin lines) computed using the inverted source parameters are compared. On the left-hand side of each seismogram the station name, component, and wave type are indicated, while to the right the epicentral distance is given in kilometers. The numbers above each waveform represent the normalized correlation (*Corr*), the normalized mean squared error (*nmse*), and the maximum amplitude in nanometers (*amp*). Since the earth model is rather uncertain, only the first *P*- and *S*-waves could be inverted successfully.

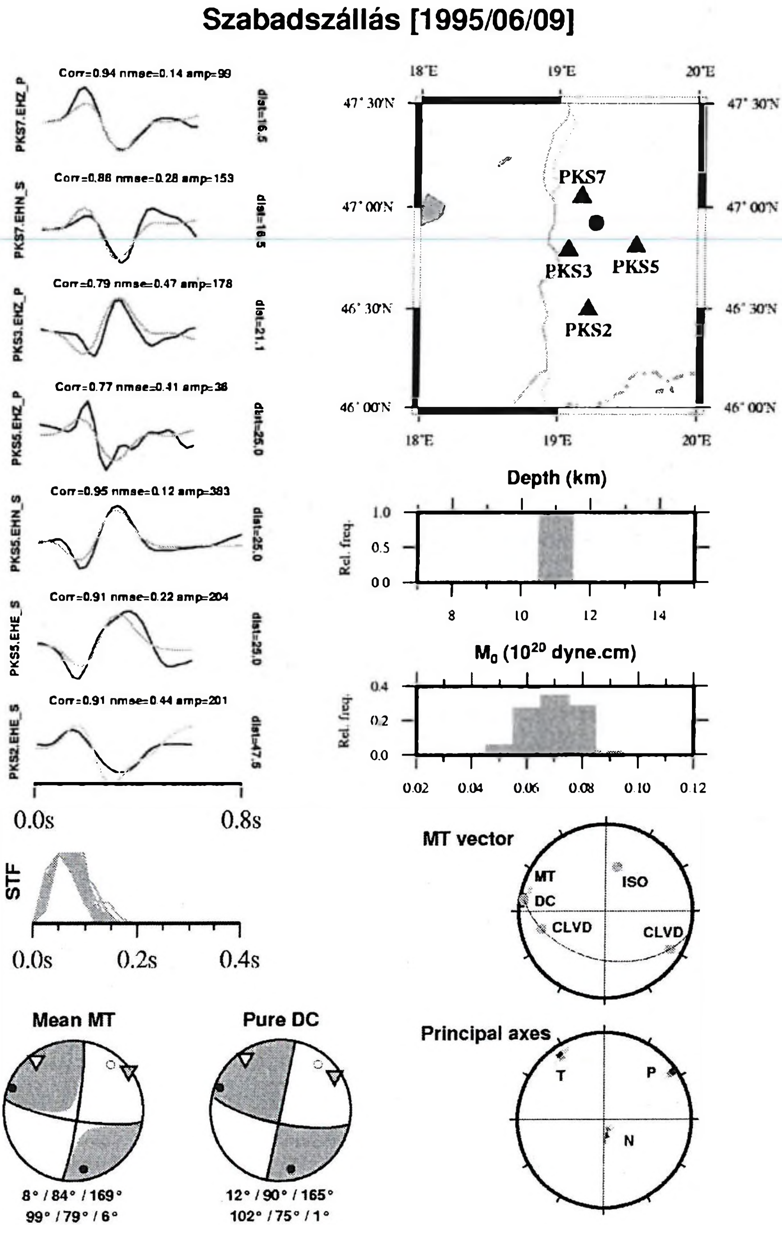

Fig. 3. Waveform comparison and moment tensor solution for the local event that occurred on June 9, 1995 near Szabadszállás, Hungary. For details, see text

3. ábra. A Szabadszállás közelében, 1995. június 9-én kipattant lokális földrengés inverziójával kapott fészekparaméterek, valamint a mért és számított hullámformák. Részleteket lásd a szövegben

For the statistical validation of the results the bootstrapping technique was used. In this study the uncertainties of the solution are estimated by inverting 300 bootstrapped data sets. The histograms of the inverted source parameters obtained after the 300 bootstrap inversions may be considered as good approximations of the corresponding confidence regions. The method of RIEDESEL and JORDAN [1989] is employed to display the histogram of the moment tensor solution. The principal vectors of a moment tensor define the tension (T), the neutral (N) and compression (P) axes, while the principal values give their magnitudes. It is a straightforward matter to construct and display the histograms of the principal axes (bottom right plot in Fig. 3). In the principal axis system, various unit vectors can be constructed using various combinations of the principal values. The vector that describes a general source mechanism is MT, a double-couple source mechanism has the vector representation DC, the vector corresponding to a purely isotropic source is the vector ISO, and two possible CLVD vectors can also be defined [JOST, HERRMANN 1989]. The histograms of the MT vectors, together with the DC, ISO, and CLVD vectors corresponding to the mean moment tensor solution are then plotted on the surface of the focal sphere. The great circle that connects the DC and CLVD vectors on the unit sphere defines the subspace on which MT must lie for a deviatoric source. The distribution of the MT solutions with respect to the DC, ISO, and CLVD vectors allows us to assess the significance of the DC, ISO, and CLVD parts of the solution.

Below the histograms of event depth and scalar moment in Fig. 3, the histograms of the MT vector and the principal axes can be seen. The histogram of the moment tensor vector (MT) contains the DC vector: thus, a pure DC may be the solution of the inversion. The tightly confined zones of the principal axes allow only a small variation of the orientation of the mechanism. The P-axis strikes NE–SW, which is in accordance with the stress field in the central part of the Pannonian Basin [BADA et al. 1998]. The plot of the 300 calculated STFs below the seismograms in Fig. 3 shows that the source time function is also well constrained and it has a simple peak with a time duration of about 0.1–0.15 s.

The beach ball representation of the mean focal mechanism is also shown in the bottom left corner of Fig. 3 (shaded area: compression; open area: dilatation; open triangle: T-axis; solid triangle: P-axis). The fault plane solution given below the beach ball corresponds to the best double-couple part of the general mechanism. Clear readings of *P*-wave polarities are also shown (open circle: dilatation; solid circle: compression).

In order to justify the pure DC solution of the problem, the selected waveforms were also inverted with the constraint that the source be a double-couple. Since this constraint is nonlinear, a grid search algorithm was used. Using the average source time function calculated from the earlier mentioned 300, we searched for the strike, dip, and slip angles giving the best fit between the observed and synthetic seismograms. The beach ball representation of the resulting fault plane solution is given next to the beach ball of the mean MT solution in Fig. 3. The pure DC solution is very similar to the DC component of the general MT solution and there is no significant difference between the waveform misfits produced by the two solutions.

The inversion results for the local event that occurred on March 28, 1996 near Szabadszállás are presented in *Fig. 4*. The epicentral coordinates of this event are almost identical to those of the previously discussed earthquake. The structure of Fig. 4 is similar to that of Fig. 3.

The uncertainty of the solution is larger than in the previous case. The MT histogram contains the locus of deviatoric solutions and it also touches the DC vector. Thus, the DC may also represent the solution of the problem. The azimuth of the P-axis is well constrained and it strikes NE–SW, which is in accordance with the stress field in this region of Hungary [BADA et al. 1998]. The source time function has only one significant peak whose time duration is about 0.1 s. The pure DC solution of the grid search algorithm is almost identical to the DC component of the general MT solution. Since the synthetic waveforms fit the observed seismograms equally well for both solutions, the pure double-couple mechanism can be considered as justified. The apparent non-DC components in the moment tensor solution are probably due to the inconsistent velocity model used for computing the Green's functions.

The third investigated local event occurred on November 23, 2000 near Kunadacs. The inversion results for this earthquake are presented in *Fig. 5*. The structure of Fig. 5 is similar to that of Figs. 3 and 4.

The uncertainty of the solution is the largest among the three discussed in this paper. The histogram of the moment tensor vector (MT) again contains the locus of the deviatoric solutions and, particularly, the DC vector. Thus, a DC may also be acceptable as the solution of the inversion problem. The azimuth of the *P*-axis spreads about 30°. However, it undoubtedly

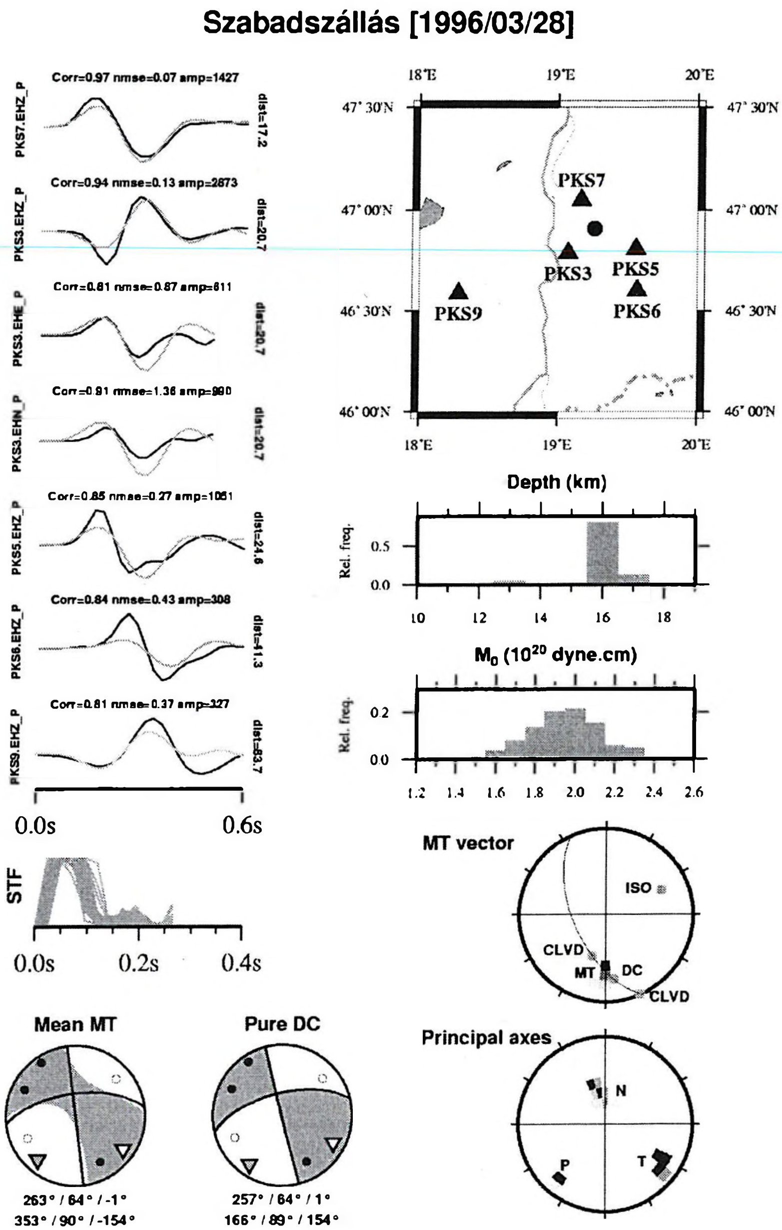

Fig. 4. Waveform comparison and moment tensor solution for the local event that occurred on March 28, 1996 near Szabadszállás, Hungary. For details, see text

4. ábra. A Szabadszállás közelében, 1996. március 28-án kipattant lokális földrengés inverziójával kapott fészekparaméterek, valamint a mért és számított hullámformák. Részleteket lásd a szövegben

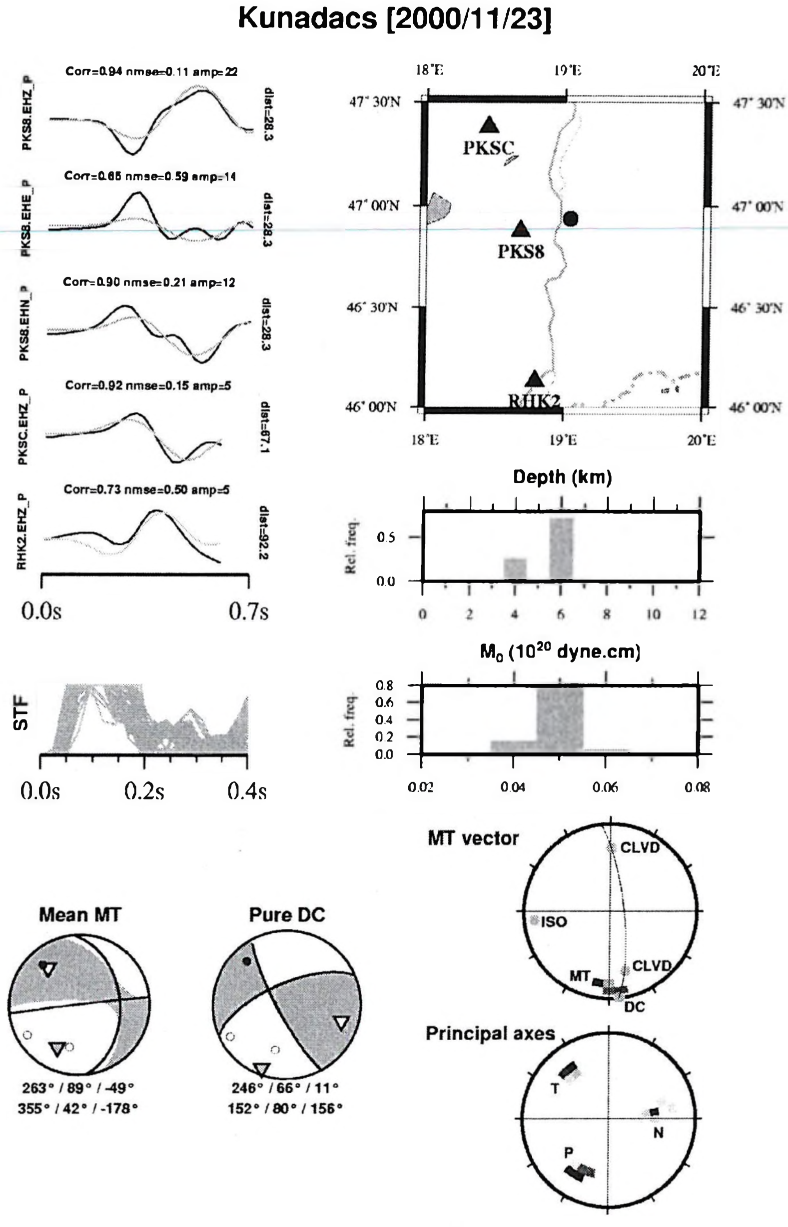

Fig. 5. Waveform comparison and moment tensor solution for the local event that occurred on November 23, 2000 near Kunadacs, Hungary. For details, see text

5. ábra. A Kunadacs közelében, 2000. november 23-án kipattant lokális földrengés inverziójával kapott fészekparaméterek, valamint a mért és számított hullámformák. Részleteket lásd a szövegben strikes NE–SW, which agrees well with the main stress pattern in this region [BADA et al. 1998]. The source time function has only one significant peak with a time duration of about 0.2 s. Although the pure DC solution of the inversion problem differs from the DC component of the general MT solution, the main features remain the same: the differences between the strike angles and the azimuths of the *P*-axes are rather small. It should also be taken into account that besides the use of the inconsistent earth model in the calculations, the main sources of the relatively large uncertainties of the solution are the irregular station coverage and the low signal-to-noise ratio. The ambient noise contaminating the low-amplitude signals is the main cause of the apparent ISO component in the moment tensor solution [SILENY et al. 1992].

7. Conclusions

The method illustrated in this paper is capable of retrieving simultaneously the hypocentral depth, the source time function, and the full seismic moment tensor of weak local earthquakes from waveform data even when the only records available are a few noisy ones. Error analysis, carried out by the bootstrap resampling technique, allows us to estimate and display the uncertainties of the event depth, scalar moment, the STF, and the moment tensor solution and its *T*-, *N*- and *P*-axes. This makes it possible to assess the significance of the DC, ISO, and CLVD parts of the solution.

The method has been applied to three local earthquakes that occurred in the central part of the Pannonian Basin. The inversion of the short-period records was successful. The non-DC components of the moment tensor solutions for the selected events are insignificant, implying the tectonic nature of the events. The source time functions obtained during the inversion process are very simple with a time duration of 0.1–0.2 seconds. The retrieved mechanisms are in agreement with the available clear readings of first-arrival *P*-wave polarities. The principal axes of the resulting source mechanisms also agree well with the main stress pattern published for the central part of the Pannonian Basin (*Fig. 6*).

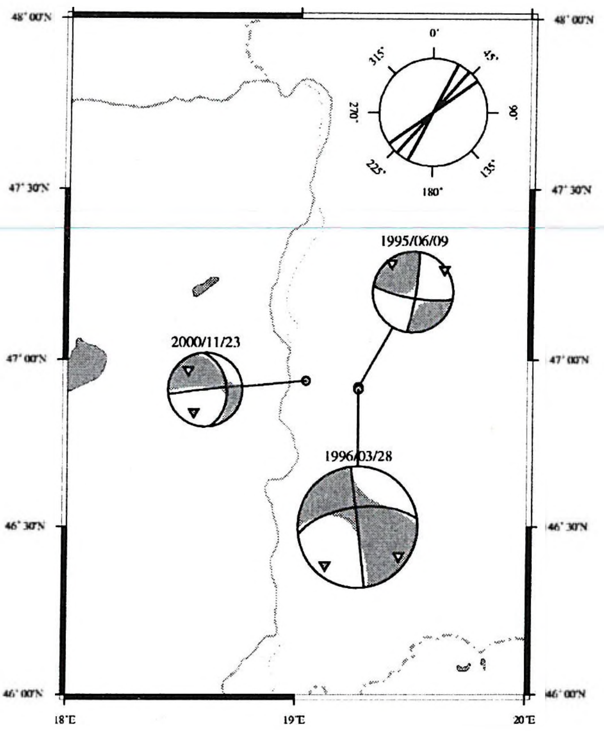

Fig. 6. Map showing the mean focal mechanisms obtained by waveform inversion. The diagram in the top-right corner of the Figure illustrates the horizontal projections of the P-axes. The azimuths of the P-axes are in good agreement with the main stress pattern published for the central part of the Pannonian Basin. Beach ball diameters are proportional to moment magnitude

6. ábra. A hullámforma inverzióval kapott átlagos fészekmechanizmusok. Az ábra jobb felső sarkában látható diagram a P tengelyek horizontális vetületét ábrázolja. A P tengelyek iránya jó egyezést mutat a szakirodalomban publikált fő feszültésgiránnyal. A "strandlabdák" átmérője arányos a momentum magnitudójával

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Lokális földrengések bootstrap inverziója a Pannon medencében

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Kis erejű lokális földrengések rövid periódusú hullámformáinak inverziójával meghatároztuk néhány, a Pannon medence területén kipattant rengés forrásmechanizmusát (momentum tenzorát). A reflektivitás módszer felhasználásával — adott földmodell mellett — számos hipocentrum mélységre szintetikus Green-függvényeket számítottunk, majd a momentum tenzor komponenseit lineáris inverzióval meghatároztuk. A forrásfüggvény alakját is megbecsültük. Azt a hipocentrum mélységet és momentum tenzort fogadtuk el megoldásként, melyek mellett a számított és mért szeizmogramok a legjobban illeszkedtek egymáshoz.

Az eredmények statisztikai jellemzése érdekében a bootstrap eljárást alkalmaztuk. Az eredményül kapott momentum tenzor komponenseinek bizonytalanságát oly módon ábrázoltuk a fókuszgömbön, hogy a DC, CLVD és izotróp összetevők statisztikai jelentősége becsülhető legyen.

A kiválasztott események inverziójával kapott momentum tenzorok csupán jelentéktelen nagyságú izotróp komponenssel rendelkeznek, ami a rengések tektonikai természetére utal. A ka-

pott forrásfüggvények nagyon egyszerű lefutásúak, hosszuk mintegy 0,1–0,2 s. A kapott mechanizmusok összhangban vannak az első *P*-hullám beérkezések polaritásával. A momentum tenzorok saját tengelyeinek irányai jó egyezést mutatnak a szakirodalomban publikált feszültségiránnyal.

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Zoltán Wéber graduated from Eötvös Loránd University, Budapest, in 1985, whereupon he became a postgraduate scholarship holder of the Hungarian Academy of Sciences (HAS) at the Geophysical Department of Eötvös University. He was awarded a C.Sc. (1991) from the HAS in earth sciences. From 1988 to 1996 he worked for the Geophysical Research Group of the HAS, Geophysical Department of Eötvös University. His main fields of interest were seismic data processing, VSP modelling and interpretation, and seismic inversion. Since 1996 he has been working at the Seismological Observatory of the Geodetic and Geophysical Research Institute of the HAS. He mainly deals with traveltime tomography and waveform inversion for focal mechanism and hypocentre coordinates. Since 1999 he has headed the Theoretical Department of the observatory. He is the national titular member of IASPEI and the ESC.