RELIABILITY OF SOURCE PARAMETERS OF LOW MAGNITUDE 
CRUSTAL EARTHQUAKES OF VRANCEA RETRIEVED BY HIGH 
FREQUENCY WAVEFORM INVERSION

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The source parameters of low magnitude shallow earthquakes occurred in the Vrancea region and surroundings were previously estimated using an inversion procedure for high frequency local waveforms. Anticipating a gross approximation of the complex structure from the study area by the 1-D crustal models used in the forward modeling, the paper aims to assess the reliability of the resolved focal mechanism and source time function by stability tests which investigate the effect of hypocenter mislocation, mismodeling of the crust, frequency content of the inverted waveforms, and internal damping of the inversion algorithm on the retrieved solution. The analysis reveals that the over-simplification of the medium structure generates large uncertainties of the inverted source parameters, consequently not all the parameters may be accepted as sufficiently accurate. The most vulnerable is the source time function. The individual moment tensor components exhibit also poor resolution. By contrast, the double couple part of the moment tensor is determined fairly well, so that it allows correlations of the tension and pressure axes with the stress field in the area.

Key words: Vrancea seismic region, low magnitude crustal earthquakes, high frequency waveform inversion, seismic moment tensor, fault plane solution, source time function.

1. INTRODUCTION

The inversion of high frequency local waveforms is the main tool in the seismic source studies focussed on the low magnitude shallow earthquakes from the Eastern Carpathians bending zone [1] – [6]. The focal mechanism and source time function of small crustal events recorded at few stations were estimated using the INPAR (INdirect PARameterization) algorithm [7], complemented with a bootstrap procedure [1], [6].

The INPAR algorithm implements the indirect parameterization of the point source: instead of determining directly the moment tensor and source time function as traditional approaches do (e.g. [8], [9]), it involves 6 independent time functions
representing the time derivatives of the components of the (full) seismic moment tensor. The first step is a linear inversion – very rapid – which determines the 6 moment tensor rate functions by taking advantage of the linear relation between them and the components of the ground displacement. The second step is a non-linear inversion, which reduces the 6 independent functions (involving a mechanism varying in time – unreasonable assumption for the weak events) to a common time function (the source time function) and a constant mechanism; in this way, the problem of reconstruction of a variable number of seismograms from a set of stations is transformed in the problem of reconstruction of 6 time functions, whose length can be controlled by their parameterization. The inverted moment tensor is decomposed afterwards into its isotropic component and deviatoric part, separated in the double couple and compensated linear vector dipole components.

The technique used in the forward modeling (the computation of the Green’s functions) was the summation of the modes of oscillation for vertically heterogeneous flat Earth models, with the body wave dispersion and the phase attenuation included [10], [11]. Being a method based on the synthesis of the complete wavefield, and therefore avoiding the necessity to decompose it into individual phases, the multimodal summation becomes particularly advantageous to generate the theoretical seismograms for the inversion of complex local waveforms, where the identification of phases may be difficult and rather uncertain.

The structure of the medium in the area from the Eastern Carpathians bend is complex due to its prominent tectonic setting. Since the construction of a 3-D inhomogeneous model, suitable to describe it accurately, is still a long term objective, a simpler alternative was accepted: the lateral variations of the structure were simulated by adopting 1-D approximations, specific for each focus-to-observation point path. The structures were constructed by integrating data available from geological and seismological measurements and studies, and are based on the series of models for the local structure around the recording stations by Răileanu et al. [12].

A bootstrap procedure [1], [6] was applied to reduce the effects of the uncertainty of the structural models and to provide robust estimates of the seismic source parameters; it consists in inverting subsets of the complete data set instead of processing the available records altogether, rejection of outliers (solutions which deviate strongly from the average), and averaging of the consistent solutions. This approach provides also a rough estimate of the uncertainty of the average mechanism from the distribution of the principal axes of the individual moment tensors accepted for averaging.

The errors of the source parameters estimated by high frequency waveform inversion are generally due to data noise, hypocenter mislocation and/or inexact structural models of the wave propagation medium (e.g. [7], [13]).

For the investigated events of Vrancea region and surroundings the noise contamination is low, therefore its effect may be neglected. Both hypocenter
mislocation and poor modeling of the medium structure result in inexact Green’s functions which deteriorate the quality of the inversion solution.

Anticipating a gross approximation of the crust when replacing the existing 3-D inhomogeneities from the study zone with 1-D structures for individual stations, the present paper aims to assess the reliability of the source parameters retrieved with over-simplified Earth models by a series of stability tests.

2. DATA

The experiments are performed with the event presented in Table 1.

The observed high-quality waveforms available are short period velocity records sampled with 50 sps (Fig.1), collected by 6 stations of the Romanian telemetered network, equipped with vertical S13 seismometers (1s free period and damping of 0.7). The epicentral distances vary between 80 and 150 km.

<table>
<thead>
<tr>
<th>Date</th>
<th>Origin time</th>
<th>Lat. [°N]</th>
<th>Lon. [°E]</th>
<th>Depth [km]</th>
<th>Local magnitude</th>
</tr>
</thead>
<tbody>
<tr>
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<td>16:36:12</td>
<td>45.84</td>
<td>27.29</td>
<td>15</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Fig. 1 – The short period velocity records (counts/s), vertical component, available for the study event - rough data; epicentral distances: (CFR) station - 100 km, Coloneşti (CLI) station - 83 km, Covasna (CVO) station - 87 km, Istriţa (ISR) station - 98 km, Muntele Roşu (MLR) station - 112 km, Topalu (TLB) station - 152 km.
The spectral analysis of the waveforms from Vrancea low magnitude earthquakes, recorded with short period instruments, reveals low energy of the signals for frequencies below 1 Hz. Therefore the use of a maximum frequency of 1 Hz in the inversion for source parameters [14] may result in losing a significant amount of the information contained in the wavetrains. On the other hand, the consideration of a high frequency (e.g. 10 Hz) requires a detailed knowledge of the structure of the medium, to model successfully the complex records. The choice of a maximum frequency of 5 Hz was considered as the best compromise solution for the study of weak crustal events of Vrancea. Hence both records and Green’s functions were filtered by a low-pass with cut-off frequency at 5 Hz.

The inverted source parameters previously obtained for the study event [1], [3], [6] are presented below.

The bootstrap fault plane solutions, average mechanism and estimate of its uncertainty are displayed in Fig. 2. The percentage of the double couple component varies across the 8 subsets, but its orientation is very stable (Fig. 2a). The distribution of the principal axes of the individual seismic moment tensors is fairly narrow (Fig. 2c), thus the estimated reliability of the average mechanism is high. The P-axis is orientated roughly NW-SE, therefore the mechanism complies with the pattern of the regional stress field in the area – that is compression from SE to NW (e.g. [15], [16]).

Fig. 2 – (a) Fault plane solutions (shaded area – compressions, white area: dilatations) corresponding to individual bootstrap trials. Observed P-wave polarities: dilatation - open circles, compression - full circles; circle dimension is proportional to reading reliability. (b) Average fault plane solution. (c) Principal axes and nodal lines for the average mechanism (full symbols and thick lines, respectively) and the bootstrap solutions (empty symbols and thin lines). T-axis - triangle up, P-axis - triangle right, N-axis - triangle left. The shaded areas enclose the individual bootstrap axes.
Fig. 3 shows the reconstructed source time functions. They are rather unstable when determined from individual station subsets (Fig. 3a). The average time function is also quite long and complex, although the main energy release is outlined in the first part of the time history (Fig. 3b).

The goal of the paper is to estimate the accuracy of the average focal mechanism and source time function by several stability tests which investigate the effect of hypocenter mislocation, mismodeling of the crust, frequency content of the inverted waveforms, and internal damping of the inversion algorithm on the retrieved source parameters.

Fig. 3 – (a) Individual bootstrap source time functions (scaling factor in the upper right corner, in units of Nm/s; vertical bar at 0.1 sec indicates the origin time computed by the location program). (b) Average inverted source time function.
3. TESTS

A common effect of an inexact velocity model of the medium is the mislocation of the earthquake hypocenter, with consequences on the reliability of the source studies.

The effect of the hypocenter mislocation, both in depth and in the horizontal coordinates, was checked by evaluating several inversions where the point of the Green’s function synthesis was located out of the point of the kinematic hypocenter. Taking into account the errors reported by the location routine, we simulated mislocation in depth of \( \pm 5 \) km and shift of the epicenter of 2.5 km in directions to NE, NW, SE and SW. The results for two bootstrap moment tensors are shown in Figs. 4 and 5. The mislocation makes the determination of the principal axes somewhat uncertain, in both cases. The T-axis is the best constrained parameter. The P-axis is less certain but its azimuth keeps a NW-SE direction, not questioning the agreement of this mechanism with the general trend of the stress field in the Vrancea region.

![Fig. 4 – Effect of mislocation. Fault plane solutions obtained when the hypocenter is shifted in horizontal plane by 2.5 km in directions to NE (a), NW (b), SE (c), SW (d), respectively in depth by 5 km up (e), and down (f). (g) Principal axes and nodal lines corresponding to the hypocenter reported by location routine - full symbols and thick lines. Principal axes and nodal lines corresponding to the perturbed hypocenter ((a) - (f)) - empty symbols and thin lines. T-axis - triangle up, P-axis - triangle right, N-axis - triangle left.](image-url)
Since we have not information on the deviation of the adopted 1-D velocity models from the real structure of the medium, we can not determine the error of the inverted source parameters due to the uncertainty of the structural models directly.

We approach the effect of the mismodeling of the crust on the resolved moment tensor by randomly perturbing the parameters of the 1-D models, and by observing the deviation of the mechanism obtained using Green’s functions constructed with the perturbed models from the unperturbed case.

The experiment is performed by randomly increasing or reducing the parameters of all the models involved (i.e. the values of layer thicknesses, and P- and S-wave velocities in 6 models for the individual stations) by 5%. An example is shown in Fig. 6. This perturbation, apparently very small, may induce significant changes of the structures, since the velocity contrast between neighbouring layers can be of this order of magnitude. The bootstrap solutions (Fig. 7) exhibit fairly well clustered T-axes; the P- and N-axes leave their plunge less constrained, but the scatter of their azimuth is low. The doubtless NW-SE orientation of P-axis allows us to conclude that the 5% model perturbation preserves the agreement of the mechanism with the regional stress field.
An additional experiment was performed to check the effect of an extreme perturbation: the velocities in a single layer were increased or reduced by 20%, while the thicknesses were randomly perturbed by the same percentage (Fig. 8). The principal axes yielded by the five bootstrap solutions plotted in Fig. 9 display a fairly tight clustering of the T-axes and a wide spread of the P- and N-axes in NW-SE direction, which indicates that this degree of model uncertainty already makes the obtained moment tensor indefinite.

Besides our limited knowledge on the medium structure, a major problem in realistic high frequency waveform modeling is the manner to approach small scale structural inhomogeneities. The consequence of an over-simplification of the Earth model, i.e. replacing the real velocity / attenuation structure by a model described by a few parameters only, is the distortion of the resolved source parameters due to using of inexact Green’s functions. Since the amount of the distortion depends on the frequency content of the inverted waveforms, we performed two tests in which the low frequencies, less vulnerable, are enhanced.
Fig. 7 – Effect of mismodeling of the medium. Individual bootstrap solutions (a), and average solution (b) perturbed by 5% of the current values of the thickness and P- and S-wave velocities in individual layers. (c) Full symbols and thick lines - average solution, empty symbols and thin lines - bootstrap solutions. T-axis - triangle up, P-axis - triangle right, N-axis - triangle left.

Fig. 8 – Example of models randomly perturbed by 20% (grey) of the current values of layer thicknesses, and P- and S-wave velocities (black).
The first test consists in inverting displacements instead of velocities (by converting the velocity into displacement before the inversion). The match of the synthetics to the observed seismograms is presented in Fig. 10, for two subsets of stations. By comparing the bootstrap mechanisms and the average fault plane solution estimated from displacements (Fig. 11) with those obtained by inverting velocities (Fig. 2), we can observe they are very similar.

The second test refers to decreasing of the maximum frequency accepted in inversion from 5 Hz to 3 Hz. Both velocity records and elementary seismograms (Green’s functions) were filtered by a low-pass with cut-off frequency at 3 Hz. An example of data fit, for maximum frequency of 3 Hz and 5 Hz, respectively, is presented in Fig. 12. The bootstrap fault plane solutions as well as the average mechanism estimated by considering a reduced high frequency content of the waveforms (Fig. 13) are consistent with the results of the inversions performed with the maximum frequency of 5 Hz (Fig. 2).

In contrast with the focal mechanism, the reconstructed source time functions seem to be more distorted by the inaccurate modeling of the structure.

Synthetic experiments simulating inversion of seismograms by using Green’s functions constructed with inexact models revealed that the features of the structure unresolved in the model are projected especially into the source time function where they appear as false peaks [17], [18].
The averaging procedure proposed in the study of Vrancea events aims to obtain representative estimates of both focal mechanism and source time function, since by averaging the incoherent signals of the bootstrap moment tensor rate functions are, at least partly, suppressed, and the coherent ones, representing averaged features of the source, are enhanced. However, the results evidence that the instability of the retrieved time history is not satisfactorily reduced by this approach (see Fig. 3).

Fig. 10 – Observed data (solid lines) and synthetic seismograms (dashed lines) reconstructed from bootstrap solutions; left - displacements, right - velocities. The numbers in the right-hand side represent the maximum amplitude (in m - left, in m/s - right) for the particular station.
Fig. 11 – Individual bootstrap solutions (a) and the average solution (b), obtained by inverting displacements. (c) Average mechanism - full symbols and thick lines, bootstrap solutions - empty symbols and thin lines. T-axis - triangle up, P-axis - triangle right, N-axis - triangle left.

Fig. 12 – Observed data (solid lines) and synthetic seismograms (dashed lines) reconstructed from a bootstrap solution; left - maximum frequency 3 Hz, right - maximum frequency 5 Hz. The numbers in the right-hand side represent the maximum amplitude (in m/s) for the particular station.

The complexity of the inverted source time functions might be a consequence of the contribution of the null subspace of the model parameters in the solution. The individual picks belonging to this subspace – which cannot be projected into the data space – should be eliminated by increasing the internal damping in the first step of the inversion algorithm. The experiments performed with varying values of the damping factor point out that the later, doubtful peaks are resolved by the data, an example is illustrated in Fig. 14; consequently, the instability of the source time function is not due to the null subspace of the model space.
Then, the source time function complexity may indicate a multiple rupture process. This hypothesis is, however, rather unlikely in the case of small earthquakes. Most probably, the instability of the time history is an artifact of the poor modeling of the structure.

Thus we may conclude that the 1-D models of the crust used in the study of the Vrancea weak events are too gross simplifications of the medium which cannot result in good estimates of the source time function.
4. CONCLUSIONS

The source parameters of low magnitude crustal earthquakes occurred at the Eastern Carpathians bending zone were estimated using an inversion algorithm for high frequency local waveforms. The 3-D inhomogeneities of the structure in the study area were substituted by 1-D models for individual stations. Since this gross simplification might be unacceptable for particular source-to-station paths, resulting in severe distortion of the retrieved source, a bootstrap-like approach was adopted, i.e. processing of subsets of the complete data set, combined with rejection of those solutions which are inconsistent with the average.

We estimate the robustness of the results of this inversion procedure by checking the effect of imperfect location of the hypocenter, mismodeling of the velocity structure of the crust, high frequency content of the wavetrains, value of the internal damping of the linear inversion on the resolved moment tensor and source time function.

The tests reveal that the over-simplification of the medium structure generates large uncertainties of the source parameters retrieved; consequently not all the parameters may be accepted as sufficiently reliable.

The most vulnerable appears to be the source time function. The inversion procedure fails in yielding fairly simple and compact average time histories, the amplitude of the spurious signals seem to be large enough to mask the signal corresponding to the real source.

As concerns the focal mechanism, the content of individual components (volumetric, double-couple and compensated linear-vector dipole, in the traditional decomposition of the unconstrained moment tensor) is also quite sensitive to the mismodeling of the Earth structure.

On the contrary, the orientation of the deviatoric part of the mechanism is fairly stable with respect to effects frequently encountered during the practice of the waveform inversion, like hypocenter mislocation and mismodeling of the inhomogeneity of the crust. Perturbations of the hypocenter coordinates by realistic location uncertainties, variation of the structural models by reasonable percentages of the values of the parameters, and increase of the weight of lower frequencies of the waveforms to be inverted do not result in significant deviations of the retrieved fault plane solutions. The double couple part of the full moment tensor is the most reliably determined source parameter, and its good resolution allows correlations of the tension and pressure axes with the stress field in the study area.

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REFERENCES


