Slowness and azimuth determination for Bucovina array (BURAR) applying multiple signal techniques

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ORIGINAL ARTICLE

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Abstract The BURAR seismic array, located in Northern Romania (Bucovina region), is designed to monitor events located in an area poorly covered by other existing seismic stations. In order to use the BURAR array for single-station locations, it is crucial to calibrate the azimuth and slowness parameters, which are currently used in array techniques to locate earthquakes, blasts or nuclear explosions. The goal of this study is to apply "f–k" and plane wave fit techniques in order to constrain the slowness and azimuth parameters at BURAR for teleseismic, regional and local events. The analysis was carried out using P and S waves recorded for events occurred between 2004 and 2008 within a radius of 50° around BURAR. The azimuth values obtained applying both methods strongly deviated from the theoretical values for regions like Central Turkey, Bulgaria, Dodecanese Islands and part of Greece, while the ray parameter deviations with respect to a 1-D IASP91 reference model are less significant. For the local events, the anomalies are smaller, except the particular case of Vrancea intermediate-depth earthquakes for which strong azimuth deviations (33.5°), both positive and negative, are observed. We investigate how these systematic deviations in azimuth are explained by the structure lateral heterogeneities which characterize the study region.

Keywords Array techniques · f–k analysis · Plane wave fit · BURAR array

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1 Introduction

Seismological arrays can be used in many different ways to study the lateral heterogeneities from the lithosphere and upper mantle structure. For this purpose, many different, specialized array techniques have been developed and applied to an increasing number of high-quality array datasets. Most of these methods use the ability of seismic arrays to measure the velocity of an incident wave front and its backazimuth. This information can be used to distinguish between different seismic phases, separate waves from different seismic events and improve the signal-to-noise ratio (SNR) by stacking with respect to the varying slowness of different phases (e.g., Schweitzer et al. 2002).

The Bucovina array (BURAR) is located in the northern part of Romania in the neighborhood

of the Ukraine border (Fig. 1). It was installed in cooperation with the Air Force Technical Applications Center (USA) and has been operating since 2002 (Grecu et al. 2002).

At the beginning, 10 seismic sensors (nine vertical component short-period and one broadband three-component) were installed in boreholes and distributed on 5 × 5 km area. The array was upgraded in 2008 when five new sensors (CMG40T) were added: three at the same positions with BUR01, BUR05, BUR09 and two at new places (BUR32 and BUR33). All the new sensors have three components and are installed at surface.

The short period components have GS-21 seismometers with 1 Hz natural frequency and 0.7 damping constant. AIM24S-1 digitizers provide 24-bit analog to digital converter (ADC) resolution of the seismometer output. The combination of seismometer gain and digitizer gain gives a value of 0.0788 nm/s/count at 1 Hz. The broadband component has a KS54000 sensor with 1 Hz natural frequency and 0.7 damping constant.

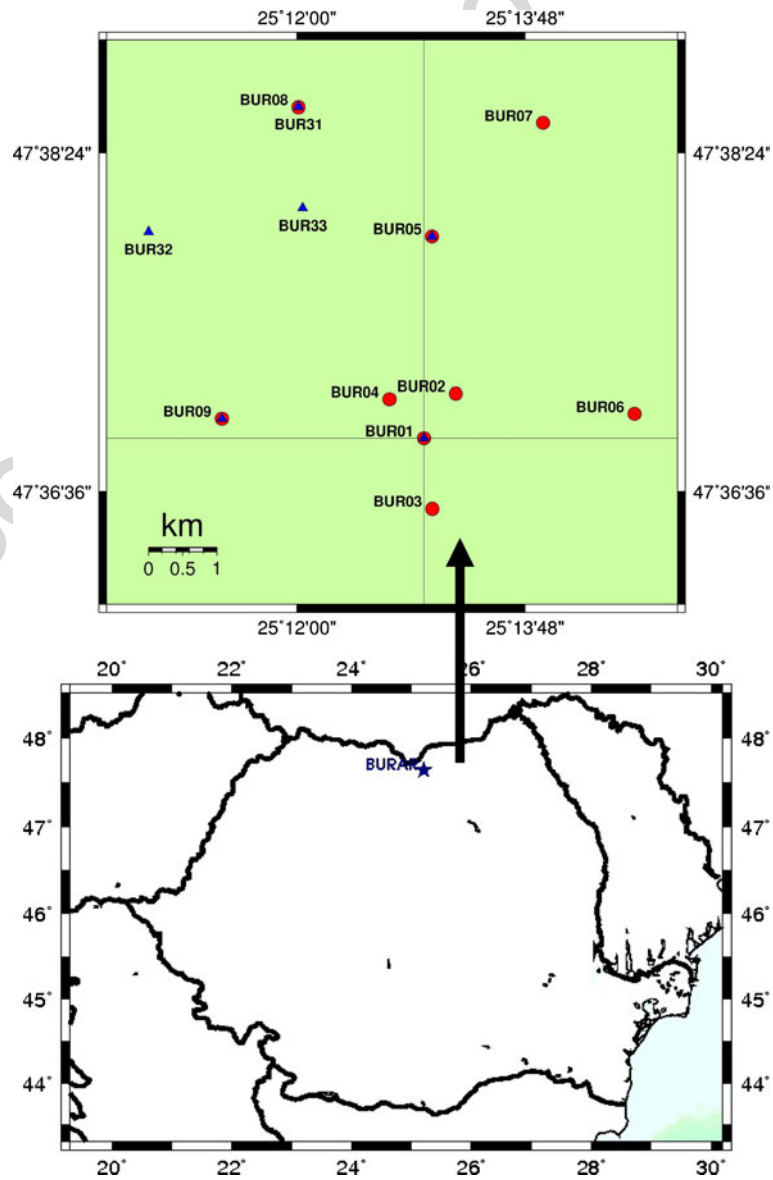

Fig. 1 BURAR location on Romania map (*bottom plot*) and array geometry (*top plot*)—*red dots* represent short period sensors and *blue triangles* represent broad band sensors

AIM24S-3 digitizers provide 24-bit A-D resolution of the seismometer output. The combination of seismometer gain and digitizer gain gives a value of 0.0404 nm/s/count at 1 Hz. The new CMG40T sensors have 1 Hz natural frequency and 0.7 damping constant and Quantera 330 digitizers provide 24-bit analog to digital converter (ADC) resolution of the seismometer output. The combination of seismometer gain and digitizer gain gives a value of 1.192 nm/s/count at 1 Hz We record continuous data with a stream of 40 samples per second (sps).

The position of the BURAR array is of highest interest since it monitors a large area with poor seismicity, including the East European Platform, the Black Sea shield, Ukraine and the northern part of Romania. It is of equal interest to detect and locate regional events in South-Eastern Europe, the Caucasus and Central Asia. Therefore, we are very interested to calibrate as much as possible the earthquake location parameters, slowness and backazimuth, using the BURAR array.

In this study, the f–k and plane wave fit analyses are used in order to evaluate the ray parameter and backazimuth values as recorded by the BURAR array. Likewise, the Velocity Spectrum Analysis (VESPA) (Davies et al. 1971) technique is applied to investigate the scattering of P waves. The frequency–wave number analysis (f–k analysis) is able to measure the complete slowness vector (i.e., backazimuth and horizontal slowness) simultaneously. The f–k analysis calculates the power distributed among different slownesses and directions of incidence (Capon 1973; Harjes and Henger 1973; Aki and Richards 1980) in the frequency domain. Plane wave fit analysis (e.g., Schweitzer et al. 2002) also measures slowness vector and backazimuth but in the time domain.

If a plane wave arrives at an array, the signal is recorded at the array stations with a certain time offset depending on the slowness vector of the wave and the position of the station in the array. These time delays are used to specify the slowness or backazimuth of the wave front. The VESPA estimates the seismic energy arriving at the array for a given backazimuth and different horizontal slowness values. Alternatively, the VESPA process can be used for a fixed slowness and varying backazimuths. The result of the VESPA process is displayed as a VESPA gram, a diagram of the seismic energy content (amplitudes) of the incoming signals as a function of slowness or backazimuth and time.

The parameters determined using BURAR records are compared with the theoretical values predicted by the source and station geometry and standard Earth models. Finally, the emphasized deviations are correlated with the tectonic features and lateral heterogeneities as observed in the Balkan region from the previous studies.

The BURAR array is located in the Eastern Carpathian Mountains at an altitude of over 1000 m, in a complex tectonic setting characterized by continental collision at the contact zone between the East European Craton and Carpathians orogen area (Fig. 2).

The Carpathians fold belt represents a segment of the Tethyan Chain placed and deformed during the Mesozoic and Cenozoic periods (Sandulescu and Visariom 2000) and consists of tectonic units emerging from the deformed lithosphere belonging to both the Tethys Ocean (the Main Tethyan Suture) and its continental margins (Southern and Eastern Carpathians).

In the Carpathians domain three types of crust can be distinguished:

- The underthrusted forelandic crust type is situated below the cover nappes of the Carpathian Flysch and belongs to the Moesian and Scythian Platforms. Its thickness is variable, having the largest values of 45–50 km in the Carpathian Arc Bend Zone.
- The second crust type is located in Transylvania, placed between the Main Tethyan Suture Zone and the “satellite” suture, being characterized by a thickness of 26–28 km. Here, the basaltic layer is normally developed, while the granite layer becomes thicker under the central part of the Transylvanian Basin.
- The third type is the Pannonian crust, which has a thickness of 24–26 km, including a thin basaltic layer (Stanica et al. 2000).

The lateral inhomogeneous structure characterizes also the entire Alpine-Mediterranean area, which is a wide and complex geophysical system

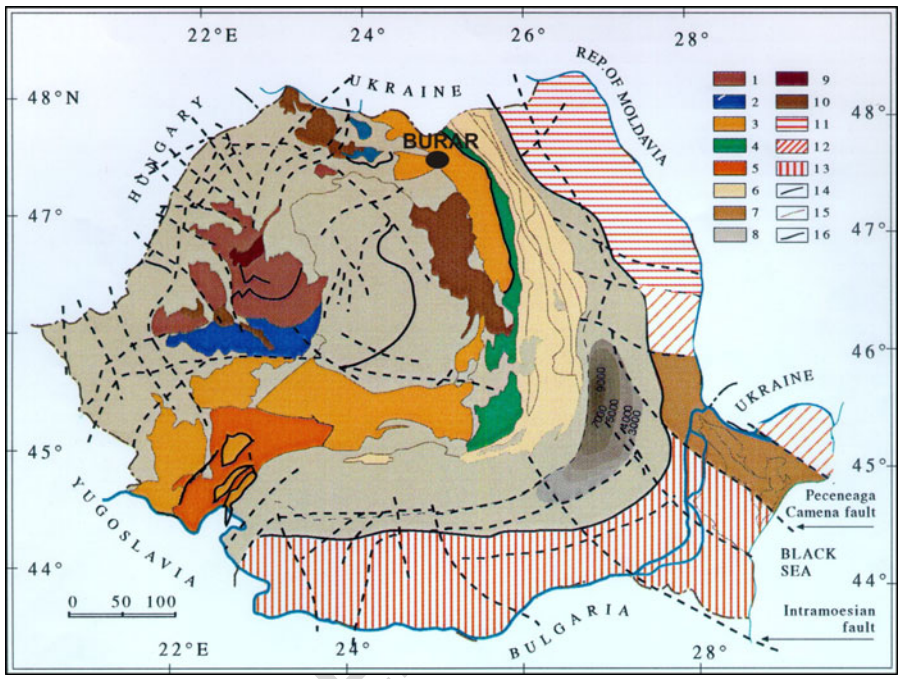

Fig. 2 Tectonic map of Romania (after Mandrescu and Radulian 1998) with location of the BURAR array—*black dot*

at the confluence of the African, Arabian and Eurasian blocks. A large amount of research has been focused on explaining and modelling the P and S wave velocity structure of the mantle in the area, ranging from regional to local scales by using different methods and data. On a regional scale, velocity structure has been studied for example by Romanowicz (1980), Spakman et al. (1993) and Bijwaard et al. (1998). Body wave and surface wave inversions were applied to determine the lithosphere–mantle structure by Panza et al. (1980), Calcagnile and Panza (1990), Zielhuis and Nolet (1994), Marquering and Snieder (1996).

2 Data processing: regional and teleseismic events

For this study we selected a number of 180 regional and teleseismic events with epicentral distance up to 50°. We considered regional events if the distance between station and source is in range of 7° up to 25° and teleseismic events if the epicentral distance is grater then 25°. The earthquakes are recorded between 2004 and 2008. The distribution of the earthquakes shows strong inhomogeneous azimuth coverage (Fig. 3). Since the majority of the earthquakes occurred in the southern part relative to BURAR, the corrections of these parameters will be better constrained for these regions. The seismic activity is strongly inhomogeneous in the study area; therefore, we cannot equally cover the entire azimuth domain.

In the case of regional and teleseismic events, the backazimuth and ray parameter values were determined for P waves using both plane wave fit and f–k techniques for a number of 180 earthquakes. The selected events were divided in earthquakes with high and medium SNR and the analysis was carried out separately. For the events with high SNR (60 events), we calculated these parameters for the S waves too. We used waveforms recorded just by the short period BURAR elements. The time windows in case of f–k analysis were manually selected with lengths between 2 and 5 s. The picks for the plane wave fit method are set manually as well. Note that the station heights differences were taken into account when applying the both analyses.

For the theoretical calculations, we adopted the standard 1-D IASP91 model (Kennett 1991) and for the parameters of the reference earthquakes the data provided by European Mediterranean Seismological Center (http://www.emsc-csem.org).

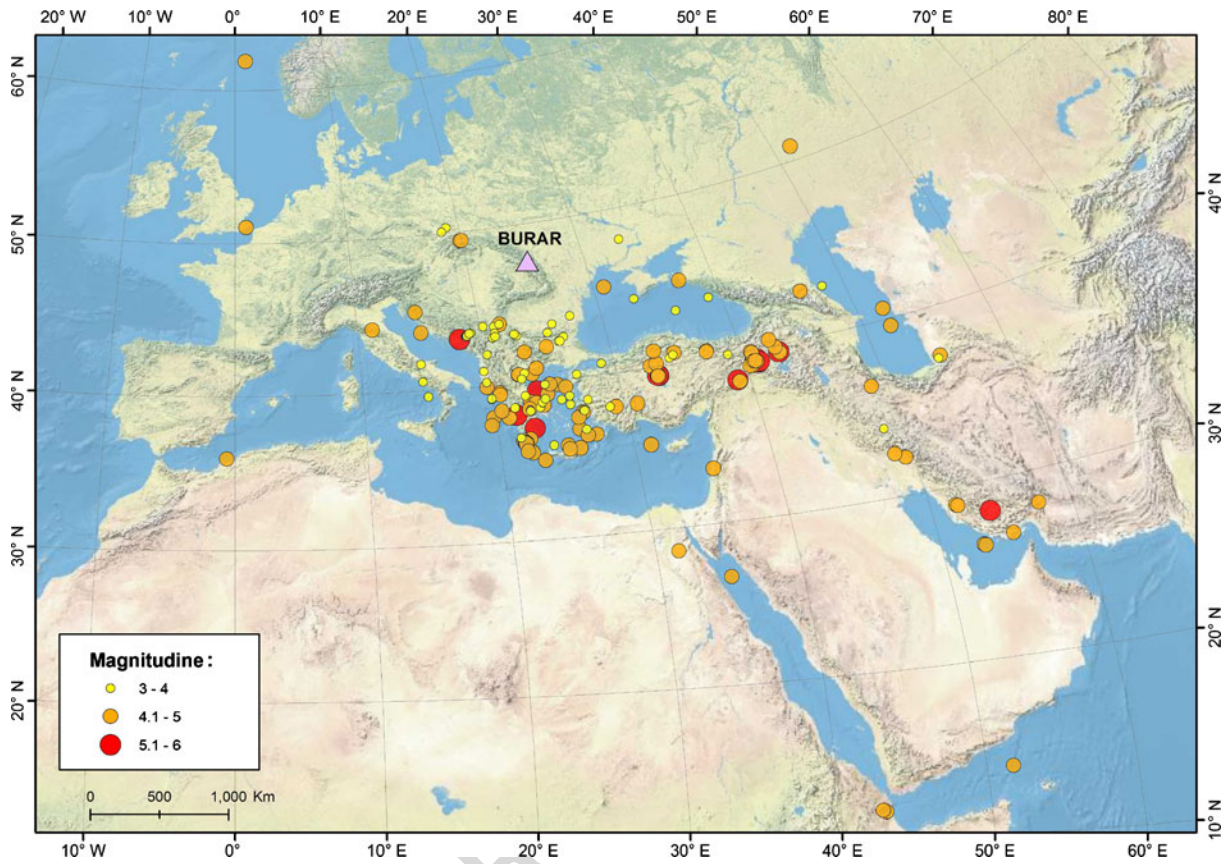

Fig. 3 The distribution of the regional earthquakes (*dots*); *triangle* shows the location of the BURAR array

To check for possible local structure differences beneath stations, we investigate the travel-times residuals at single stations for the events with best signal-to-noise ratio and did not find any systematic delays.

For the f–k analysis (Fig. 4) of P waves, we distinguish two azimuthal segments with major deviations: one is situated between 70° and 150° where negative backazimuthal deviations are prevalent signifying deviations of the seismic rays towards east as compared with the theoretical ray paths; the other is situated between 160° and 200°, where positive backazimuthal deviations are prevalent, showing deviations to the west of the seismic rays. No systematic deviations are noticed in the interval 200–260° due to the diminishing detection capacity or poor seismicity.

The plane wave fit analysis applied for the same events (P waves) shows practically a similar distribution of the backazimuthal deviations (Fig. 4)

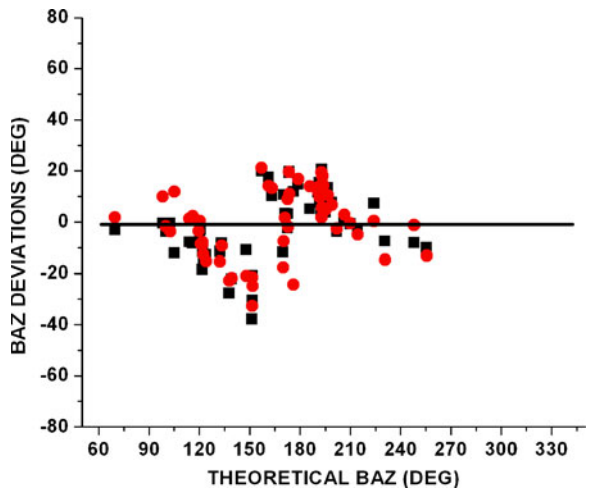

Fig. 4 Backazimuth deviations resulted from f–k (with *black squares*) analysis and plane wave fit analysis (with *red dots*) in the case of P waves for the events with high SNR

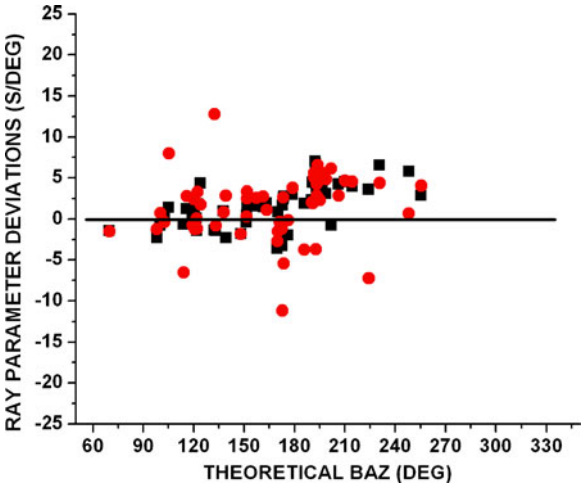

Fig. 5 The ray parameter deviations resulted from f–k (with *black squares*) analysis and plane wave fit analysis (with *red dots*) in the case of P waves for the events with high SNR

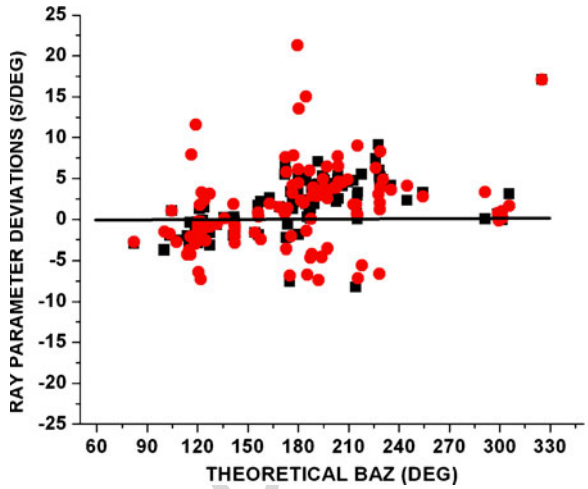

Fig. 7 The ray parameter deviations resulted from f–k (with *black squares*) analysis and plane wave fit analysis (with *red dots*) in the case of P waves for the events with medium SNR

with generally smaller deviation values than those resulted from the f–k analysis (Fig. 5).

The investigation of the ray parameter deviations shows values around zero up to 180° and slightly tendency for positive values from 180° to 260°. Figures 6 and 7 show the results of the f–k and plane wave fit analysis when considering the events with medium SNR; in fact, these are represented by events for which P waves entries are not characterized by impulsivity. The same patterns are obtained as for the high SNR events, characterized by a clear impulsive P phase. An azimuth interval with no earthquakes detected previously (280° to 320°) has this time a few earthquakes recorded. This time the azimuth deviations are higher in case of plane wave fit analysis.

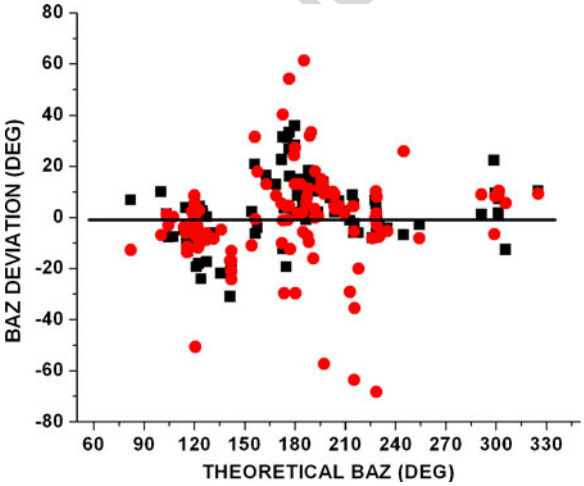

Fig. 6 Backazimuth deviations resulted from f–k (with *black squares*) analysis and plane wave fit analysis (with *red dots*) in the case of P waves for the events with medium SNR

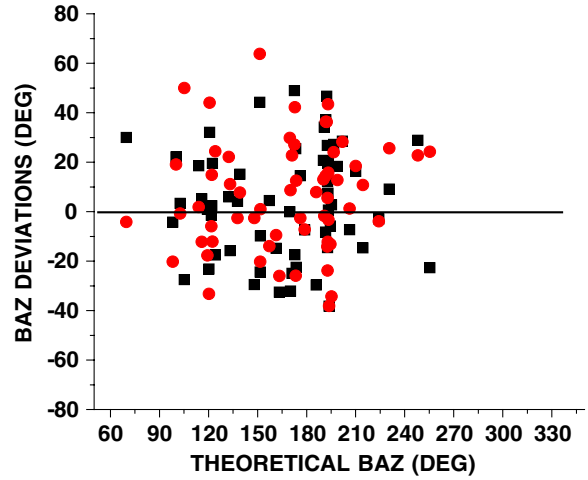

Fig. 8 Backazimuth deviations resulted from f–k (with *black squares*) analysis and plane wave fit analysis (with *red dots*) in the case of S waves for the events with high SNR

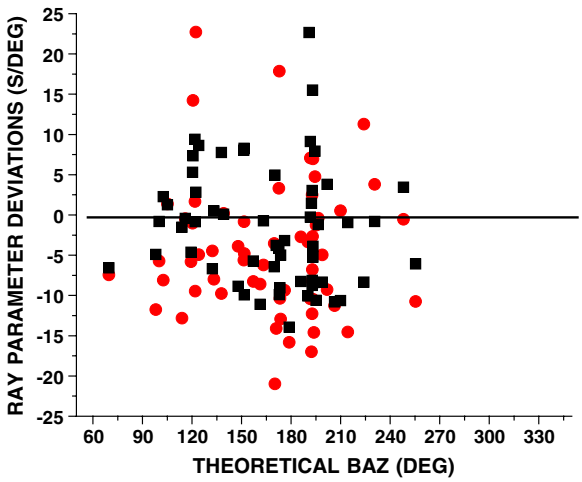

Fig. 9 The ray parameter deviations resulted from f–k (with *black squares*) analysis and plane wave fit analysis (with *red dots*) in the case of S waves for the events with high SNR

Our investigation shows that the plane wave fit analysis is very sensitive to the SNR and is not appropriate to constrain the deviations provided by the moderate earthquakes. Different filtering ranges were tested in order to increase signal to noise ratio. For all events, a Butterworth band pass filter between 0.8 and 3 Hz can be adopted as most appropriate for both techniques. Note that with increasing the frequency range in case of Butterworth bandpass filter, the onsets were distorted and became unclear what makes the power of the signal to be lower. The filtering application leads to an increase of the signal to noise ratio with an order of 3.

We applied both techniques for S waves in the case of events with high SNR. It is quite difficult to appreciate arrivals of different phases (e.g., Sg, Sn) and the corresponding errors are higher than in the case of P waves. The distributions of backazimuth and ray parameter deviations are more scattered than in case of P waves for events with high SNR. Both deviations are better defined using f–k analysis than plane wave fit technique (Figs. 8 and 9) because the last one requires accurate identification of arrivals. For S waves, it is difficult to identify any tendency in backazimuth and ray parameter deviations.

The VESPA diagrams provide a way to identify the direction of waveforms propagation and the scattering suffered by the P waves and can be used to sustain our statements concerning the backazimuthal deviations for P waves. The time length used for the VESPA plots was up to 40 s which contains a small time window before the first onset and the rest of the plotted seismic signal. The waveforms have been filtered with

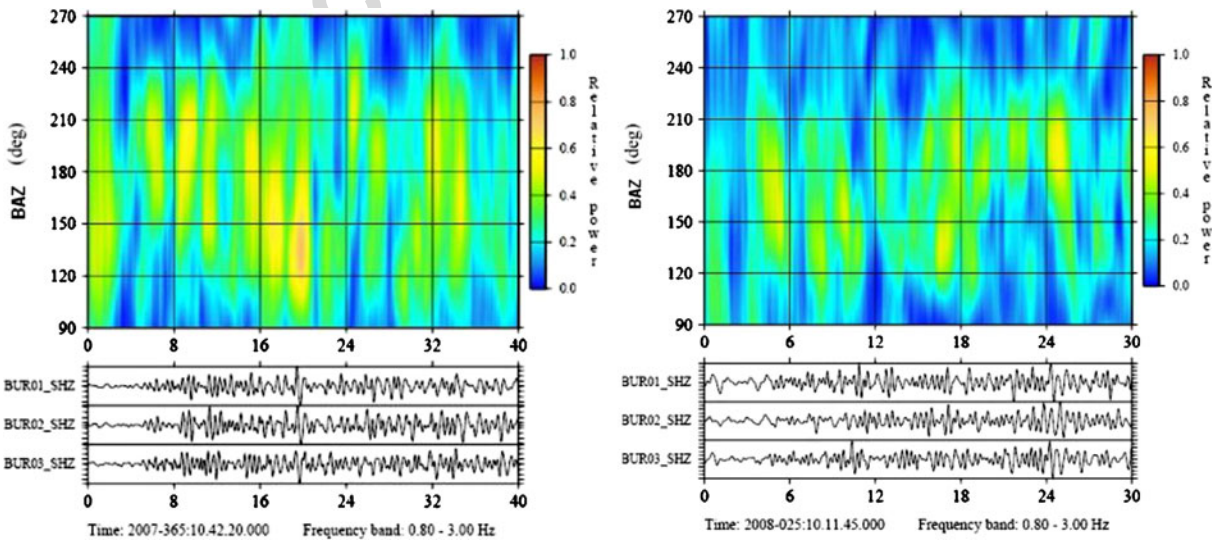

Fig. 10 An example of VESPA gram for the earthquake occurred in the Aegean Sea on 12/31/2007 (*left side*) and an example of VESPA gram for the earthquake occurred in Bulgaria on 01/25/2008 (*right side*). Distinguished outset phases can be associated in the seismogram as regions with high incoming energy

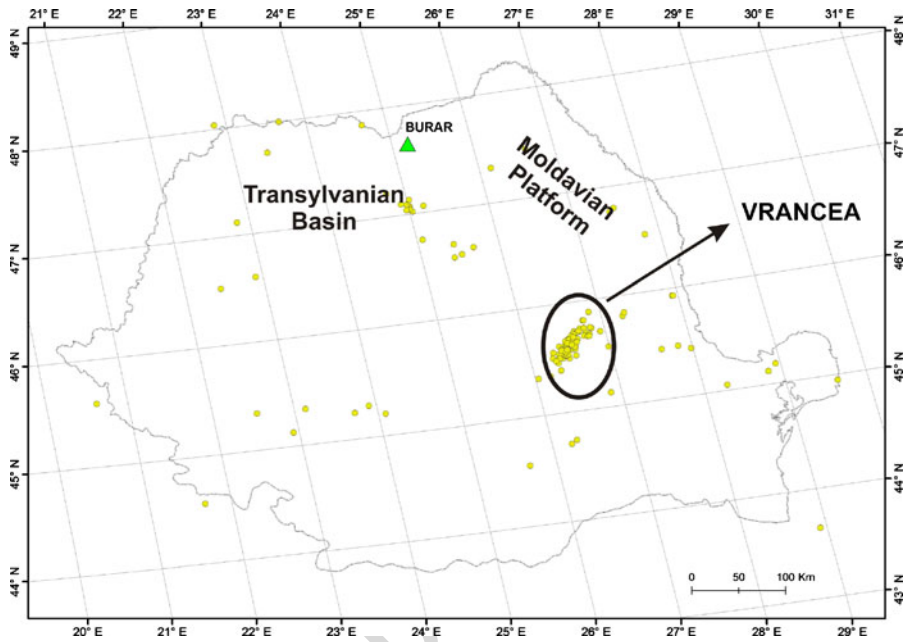

Fig. 11 The distribution of the local earthquakes (*dots*); *triangle* shows the location of the BURAR array

a Butterworth band pass filter between 0.8 and 3 Hz. Two examples are given in Figs. 10 and 11 for an earthquake in the Aegean Sea (M_w = 4.0) and another one which occurred in Bulgaria (M_L = 4.0). In both cases the backazimuth identified in the VESPA gram (203.39° for the first event and 204.29° for the second one) differ by about 30° from the theoretical values (171.71° in the first case and 172.91° in the second case). The deviations (around 32°) are of the same order as the deviations obtained by f–k and plane wave fit analyses.

3 Data processing: local events

The local events are distributed within a radius of about 4.5° around BURAR. We selected a number of 121 events with sufficient SNR (>5) for the BURAR recordings. We treated separately the shallow earthquakes (52 events with depths between 0 and 38 km) and intermediate-depth earthquakes (69 events with depths situated between 69 and 160 km). We used waveforms recorded just by the short period BURAR elements. All the intermediate-depth events are coming from the Vrancea seismic source, located beneath the South-Eastern Carpathians Arc bend, at about 350 km epicentral distance from the BURAR array (Fig. 11). Because the SNR has generally medium values, we used only f–k analysis and only P waves.

The backazimuth anomalies (Fig. 12) are of the same order as for the regional events, but this time we cannot identify segments with systematic deviations. The ray parameter anomalies (Fig. 13) are generally small (below 7 s/deg) so that we conclude that for the crust at local scale the in-

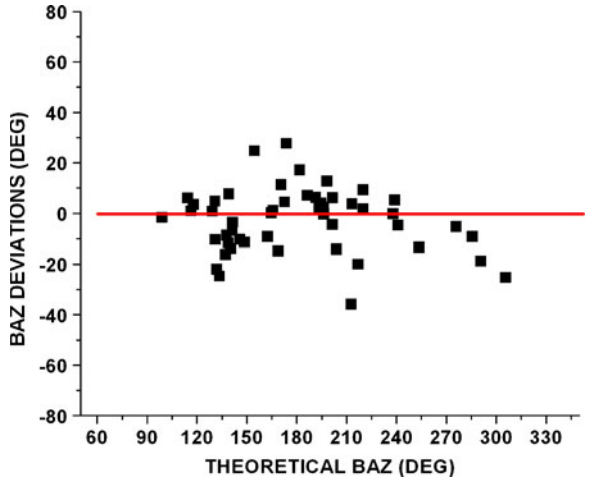

Fig. 12 Backazimuth deviations for the shallow events

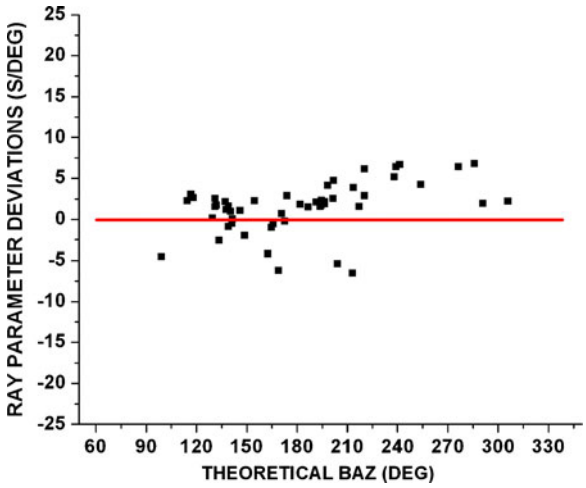

Fig. 13 Ray parameter deviations for the shallow events

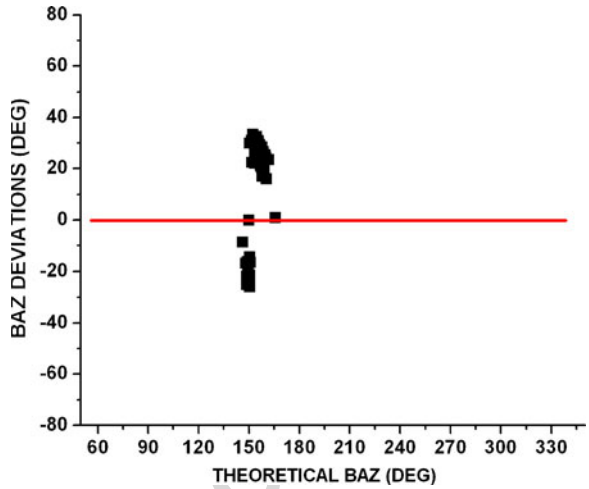

Fig. 15 Backazimuth deviations for the intermediate-depth events

homogeneities are not so strong as for the entire lithosphere as revealed at regional scale.

At the same time, the VESPA grams outline backazimuthal deviations smaller than in the case of regional events. Two examples are given in the Fig. 14 where the theoretical values of backazimuths are 165.12° for the first event (left side) and 186.65° for the second one (right side), while we found from the diagram the values of 164.91° in the first case and 193.66° in the second one.

The intermediate-depth events represent a particular case considering their extreme concentration in space, and also the important backazimuthal deviations (Fig. 15) clustered in two separated groups. The group with negative anomalies is traveling to BURAR through the Moldavian Platform, while the group with positive anomalies is traveling to BURAR through the Transylvanian Basin. Apparently, the azimuth

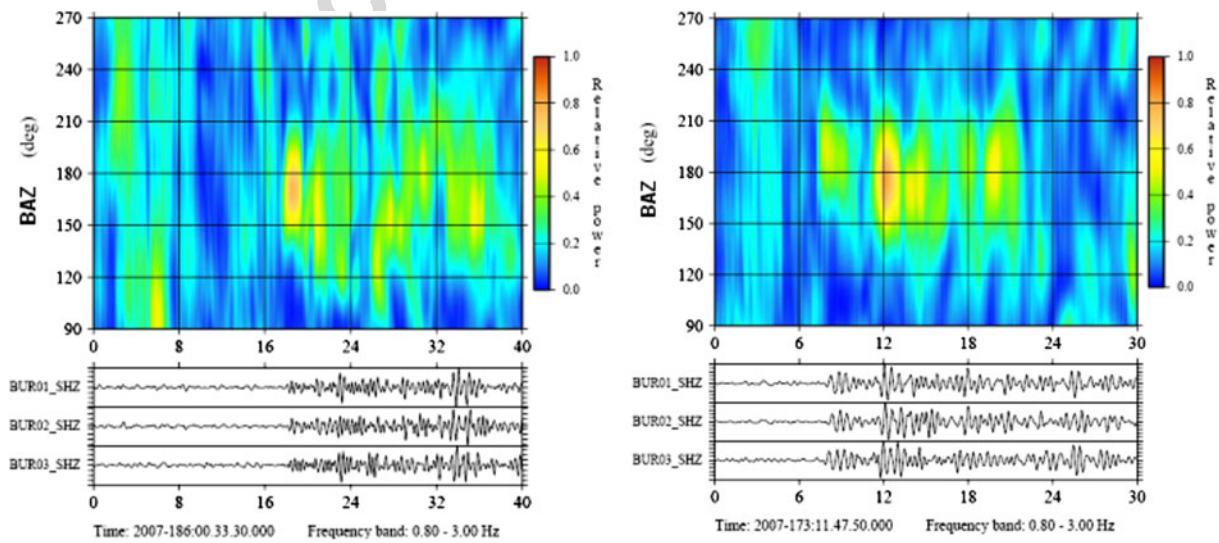

Fig. 14 An example of VESPA gram for the earthquake occurred in Muntenia region (southeastern part of Romania) on 07/05/2007 (*left side*) and another for the earthquake occurred in Transylvania region (western part of Romania) on 06/22/2007 (*right side*)

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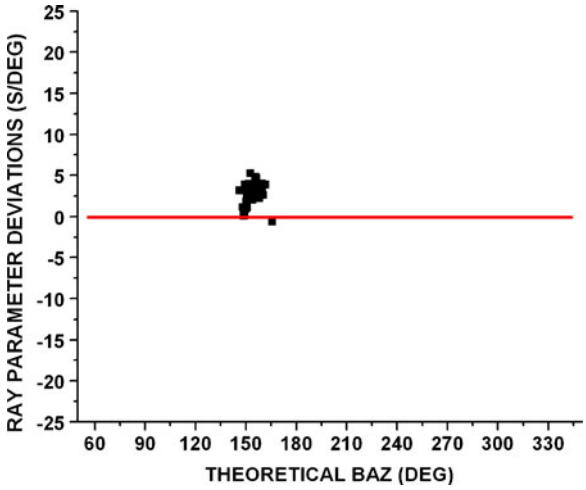

Fig. 16 Ray parameter deviations revealed in case of the intermediate-depth events

deviations correlate with the epicentral position (Fig. 17): negative anomalies for the earthquakes produced in the northeastern part of the Vrancea area and positive anomalies for the earthquakes produced in the southwestern part of the Vrancea area.

The ray parameter deviations are positive but significantly smaller (Fig. 16) and can be hypothetically explained by the structural heterogeneities below the array (Fig. 17).

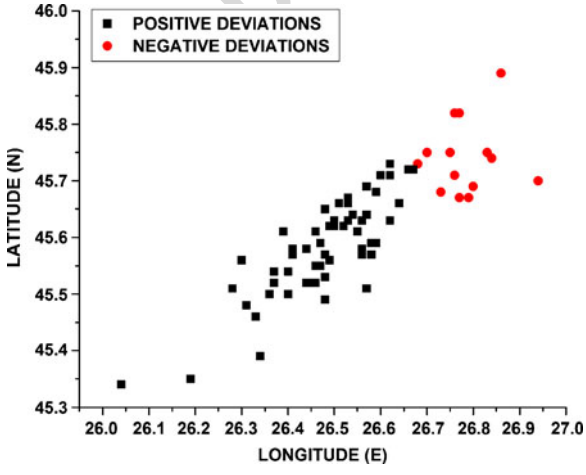

Fig. 17 Distribution of the epicenters of Vrancea earthquakes with the associated backazimuth deviations

4 Conclusions

The present paper describes a quality analysis performed on data recorded by the Bucovina Array (BURAR), situated in the northern Romania. The application of plane-wave fit and f–k techniques to local, regional and teleseismic events outlines significant anomalies in backazimuth and ray parameter measurement as compared with the values predicted by standard IASP91 1-D model. VESPA-grams of a few selected events confirm these results.

High backazimuth deviations are found for seismic events from the southern sector, changing abruptly from negative to positive values between 150° and 160°. They are more pronounced in the case of regional and teleseismic events than local events. Since these deviations create severe problems regarding the detection capabilities of the BURAR array for the events from the southern sector, they should be considered as corrections when using BURAR array in location procedures.

The purpose of this study limits itself to define the deviations relative to a standard 1-D model (IASPEI91) using available recordings and different techniques of investigation and correlated them only qualitatively with the seismotectonic settings of the region. Certainly, a major step forward in the future work will be to explain these important anomalies by a local/regional 3-D model.

The bending of the rays coming in the segment 100–140° shows a lateral increase of the velocity to the east (East European Platform), while the bending in an opposite direction for the rays coming in the segment 150–200° shows a lateral increase of the velocity to the west. We assume that the bending effects are larger in the mantle than in the lithosphere because they are prominent in the case of regional events.

As concerns the ray parameter deviations, they are not as evident as the backazimuth deviations. The ray parameter anomalies for regional and local events may be not significant, as (1) the incidence angle for P_n does not change with distance and (2) the comparison with IASPEI91 may be too much simplified, considering the complex geological situation of the study area. For example,

the encounter of high-velocity material descending in the asthenosphere beneath the Vrancea region could induce negative anomalies of the ray parameter for the rays passing through this zone.

It is well known that in many cases, the observed direction deviations are caused by local structure directly beneath the stations. Our tests for BURAR using single station travel time delays for the events with high signal-to-noise ratio do not indicate systematic delays, so that, to a first approximation, we can assume that lateral differences in the local structure beneath the array do not significantly influence our interpretation.

The main conclusion of our investigation is the observation of considerable anomalies when using BURAR array data for regional and teleseismic events situated in the southern domain as compared with standard IASPEI91 model. Clearly, they show significant heterogeneities in the mantle along this sector and require insertion of array corrections for location procedures. At the same time, the raw measurements of azimuth and ray parameter as input for corrections contain considerable scatter. Therefore, future efforts are recommended to remove outliers and to define smoothed functions over azimuth and ray parameter for correction procedures (either as table or fitted analytic function). Alternatively, a list of selected, representative events can be considered, where the closest match can be transferred to the new event. The increase of available database for BURAR and the improving of interpretation by considering regional 3-D modeling are crucial steps to implement the results of the present work.

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