Originally published as:

Donner, S., Krüger, F., Rößler, D., Ghods, A. (2014): Combined Inversion of Broadband and Short-Period Waveform Data for Regional Moment Tensors: A Case Study in the Alborz Mountains, Iran. - *Bulletin of the Seismological Society of America*, 104, 3.

DOI: <http://doi.org/10.1785/0120130229>

Combined Inversion of Broadband and Short-Period Waveform Data for Regional Moment Tensors: A Case Study in the Alborz Mountains, Iran

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Abstract In this study, we suggest a novel approach for the retrieval of regional moment tensors for earthquakes with small to moderate magnitudes. The first modification is the combined inversion of broadband and short-period waveform data. The broadband waveforms are inverted in a frequency range suitable for surface waves, whereas for the short-period data a frequency range suitable for body waves is applied. The second modification is the use of first-motion body-wave polarities to select the most probable solution out of all solutions from inversion. To combine three different criteria for selecting the most probable solution (i.e., residual from inversion, double-couple content of solution, number of nonmatching first-motion body-wave polarities), the L2 norm is applied to the normalized parameters. We chose five earthquakes within the Alborz mountains, Iran, as a case study ($3.1 \leq M_w \leq 4.1$). In this area, several factors exacerbate the difficulty of performing inversion for moment tensors, for example, a heterogeneous station network and large azimuthal gaps. We have demonstrated that our approach supplies reliable moment tensors when inversion from broadband data alone fails. In one case, we successfully retrieved a stable solution from short-period waveform data alone. Thus, our approach enables successful determination of seismic moment tensors wherever a sparse network of broadband stations has thus far prevented it.

Introduction

Teleseismic inversion for moment tensors of larger earthquakes ($M_w \geq 5.0$) is a standard procedure in seismology. The Global Centroid Moment Tensor (Global CMT) catalog is one of the most important sources for global earthquakes and has provided seismic moment tensors since 1976. Also, the U.S. Geological Survey (USGS) routinely analyzes waveform data of global earthquakes for moment tensors. Such catalogs are very useful for global studies, such as investigations of plate movements, stress maps, and subduction zone geometries. However, tectonically active regions with a high hazard potential, and therefore high economic and mortality risk, need a more focused investigation of moment tensors to understand their seismotectonics in more detail (e.g., [Kinscher et al., 2013](#)). Such investigations also need to include moment tensors of moderate to small earthquakes ($3.0 \gtrsim M_w \gtrsim 4.0$) observed on a regional scale to enlarge the database for seismotectonic investigations.

For the European region, the European–Mediterranean Seismological Centre is an important source for regional

moment tensors. They bundle information provided by 18 different seismological institutes throughout Europe and beyond, such as the GEOFON Program in Germany, the Swiss Seismological Service in Switzerland, the Istituto Nazionale di Geofisica e Vulcanologia in Italy, and the Kandilli Observatory and Earthquake Research Institute in Turkey. Additional suppliers for regional seismic moment tensors beyond Europe are, for example, the Berkeley Seismological Laboratories in California, United States, the National Research Institute for Earth Science and Disaster Prevention in Japan, and GNS Science in New Zealand.

Many more institutions exist worldwide providing global and regional moment tensors. However, they all report moment tensors for regions in which a dense network of broadband stations have already been established and is often continuously expanded. For regions with only a sparse network of broadband stations but significant seismicity, moment tensors are often missing. Especially when the distribution of these few stations do not cover the azimuthal range evenly, it is very difficult to retrieve reliable moment tensors. With this study, we address the problem of sparse station coverage, especially for smaller events, and suggest

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Figure 1. Location of seismic station networks in Iran. The outlined area in the north is the Alborz mountain region. Large and small reversed triangles give the locations of broadband (BB) and short-period (SP) stations of the Iranian national networks, respectively. The inset shows an overview map on a regional scale.

a novel approach. The modified approach is still based on widely known standard inversion techniques, but subtle modifications in the processing bring an advantage for difficult data situations, especially with respect to smaller earthquakes.

A comprehensive retrieval of moment tensors of smaller magnitude earthquakes on a regional scale faces several difficulties. The most common problem is the availability of an appropriate velocity model with which to model the waveforms. Regional waveforms, especially of smaller earthquakes, are more complex and characterized by higher frequencies (lacking the very low frequencies usually used for inversion), which are more sensitive to structural details of the crust, compared to teleseismic ones. Another challenge is the availability of data. Sparse broadband networks can considerably lower the possibilities of successful inversion for moment tensors. The influence of both factors is even more severe for events with smaller magnitudes, because they radiate less very-low-frequency energy, which decreases the signal-to-noise ratio (SNR) of the data and thus the amount of available data.

We propose the simultaneous inversion of broadband and short-period waveform data to retrieve stable regional moment tensors from moderate to small earthquakes. We show that combining both types of data leads to more stable solutions with better constrained centroid depths. Also, the seismic moment M_0 is precisely determined from both types of data. In addition, we use the available first-motion body-wave polarities as a constraint to choose the most reliable solution among all solutions explaining the data from inversion.

As a case study, we selected five events within the Alborz mountains (Fig. 1) of which one was resolved by

short-period waveform data alone. The Alborz mountains are an intracontinental, double-verging mountain range within the Alpine-Himalayan orogen affected by the northward movement and collision of the Arabian plate with stable Eurasia (e.g., Ballato *et al.*, 2010). This mountain range absorbs approximately one-third of the 22 mm/yr north-northeast-south-southwest oriented shortening via a complex system of range-parallel thrust and strike-slip faults (Vernant *et al.*, 2004). It has been studied very well by geomorphologic methods (e.g., Berberian, 1974; Jackson *et al.*, 2002; Allen *et al.*, 2003). Detailed seismic source studies, however, are rare due to the above mentioned problems. Two of the selected events in this study have been analyzed previously using only broadband data (Donner *et al.*, 2013). They are aftershocks of the M_w 6.2 Baladeh event of May 2004.

In this paper, we demonstrate the advantage of using broadband and short-period waveform data together for the retrieval of moment tensors. We further constrain the solution by using first-motion body-wave polarities. We begin with a brief description of our approach and the data processing. Then, we show the results of five earthquakes within the Alborz mountains ($3.1 \leq M_w \leq 4.1$) and compare the solutions of broadband data alone with the ones from combined data. Finally, we end with a short discussion of our results.

Data and Working Procedure

Approach to the Procedure

Since 2004, a wide network of three-component broadband stations, the Iranian National Seismic Network, was established in Iran with increasing numbers of stations over time. It is operated by the International Institute of Earthquake Engineering and Seismology. The stations are equipped with Guralp CMG-3T seismometers with a corner period of 100 s, recording at a sample rate of 50 Hz. This network permits the inversion of broadband waveform data for seismic moment tensors with standard methods as described, for example, in Jost and Herrmann (1989) and Aki and Richards (2002). However, especially in the early years, data from only a few stations were available. Within the Alborz mountains, only six stations are installed, three of which are in the central Alborz. Together with the large azimuthal gap due to the South Caspian Basin (SCB), successful inversion for moment tensors with standard methods often show instabilities and are in some cases not reliable enough for seismotectonic interpretations (Donner *et al.*, 2013).

The Iranian Seismic Center (IRSC) of the Institute of Geophysics, Tehran University (IGUT) operates the Iranian Seismic Telemetry Network. It mostly consists of short-period three-component SS-1 Kinematics seismometers. The instruments have a corner period of 1 s and record data at 50 Hz. The network comprises several telemetry subnetworks that are connected to a central processing station in Tehran via Internet and satellite connections. The station

Figure 2. The concept of corner frequency f_c . Plateaus of seismic moment correspond to given moment magnitudes. The thick, black line indicates the corner frequency according to magnitude. Gray lines indicate the approximate frequency ranges recorded by broadband and short-period stations and the approximate frequency ranges radiated by surface and body waves. The gray dashed line gives the range, which is usable only after instrument correction. Modified after Aki and Richards (2002).

spacing of each subnetwork is about 50 km or less and thus provides very good azimuthal coverage within each subnetwork.

Typical difficulties in using short-period data include making a proper instrument correction, estimating the corner frequency of the analyzed earthquake versus the frequency range recorded by the instrument, and assessing the validity of the structural model (e.g., 1D model versus 3D effects, such as scattering). The short-period stations of IGUT have a flat response function to ground velocity for frequencies greater than their corner frequency, which is 1 Hz. They are feasible for all applications in which the signal of interest is mainly above 0.1–0.3 Hz (Bormann, 2002). To make waveform data usable for waveform inversion, it is necessary to correct them for the instrument; that is, the response function of the instrument is deconvolved from the data (Fig. 2). Successful instrument correction and therefore the question of how far the lower frequencies of the short-period data are usable for inversion depends on the correctness of the instrument parameters (e.g., damping, amplifier gain, A/D converter sensitivity, poles and zeros). More information on the instrument correction of the Iranian short-period stations is in a later section.

Inversion for moment tensors is restricted to waveform amplitudes below the corner frequency of the earthquake (Fig. 2). Otherwise, effects due to the extent of the source cannot be excluded and the point-source assumption on which the inversion is based becomes invalid. The corner frequency decreases with increasing earthquake magnitude. Smaller earthquakes at higher frequencies generally have a better SNR and more often satisfy the point-source condition (Fig. 2). From this point of view, it would be beneficial to also incorporate short-period waveforms of smaller earthquakes into the inversion for moment tensors. On the other hand, to model the higher frequencies well enough for waveform inversion, the velocity structure of the region under study needs to be properly known, because the frequency is inversely proportional to the wavelength. Higher frequency waveforms are thus much more sensitive to small-scale features of the structure than lower frequency waveforms. Weaknesses in the velocity model are the main reason for the lower magnitude boundary for which inversion for moment tensors is possible (e.g., Dreger and Helmberger, 1993).

Because of the reasons mentioned above, short-period waveforms are usable only for small magnitude events. Their waveforms need to be inverted in a frequency range where possible inaccuracies of the velocity model might have a larger effect on the inversion result (e.g., Rößler et al., 2007). However, Ardeleanu et al. (2005) have been successful in determining at least a gross estimate of the moment tensor from short-period waveform data alone, even when using a simple velocity model. Nevertheless, using additional short-period data can decrease the azimuthal gap and enhance the station distribution. It also expands the amount of available data and can thus help to better constrain the inversion for moment tensors.

Following the approach of Zahradník et al. (2001), we used first-motion body-wave polarities as an additional constraint for the selection of the most reliable solution among all possible ones from the inversion. Moreover, we used all definable polarities from broadband and short-period data instead of only the very obvious ones. Thus, we were able to distinguish between possibly competing solutions.

Data Processing

We deconvolved all data by the instrument response then integrated and scaled the results to true ground displacement. To separate *SV* and *SH* wave components, we rotated the data into the *ZRT* coordinate system. The broadband data are corrected for the instrument response to true ground displacement down to a frequency of 0.01 Hz, where the instrument characteristics are very well known. The short-period data were corrected for the instrument response down to 0.1 Hz. In Figure 3 we compare the corrected waveforms from a broadband (DAMV) and short-period station (DMV), which are located within a distance of about 6 km. The data are from the M_w 3.7 earthquake of 20 December 2006. Figure 3a shows the raw data, which have been corrected

Figure 3. A comparison of instrument correction between broadband and short-period stations. DAMV and DMV are broadband and short-period stations, respectively, within a distance of only 6 km in the center of the Alborz mountains. The event-station distances are 20 km (DAMV) and 26 km (DMV). The corrected, integrated, and rotated displacement seismograms are shown at the top; the bottom contains an additional 0.1–1 Hz band-pass filter, which is the frequency range that both types of stations record uniformly. All amplitudes are scaled with the same factor. Vertical lines mark the onsets of *P* and *S* waves.

for the instrument response, integrated to displacement, and rotated to the *ZRT* coordinate system. Figure 3b shows the same data with an additional band-pass filter between 0.1 and 1 Hz. All amplitudes are plotted with the same scaling factor. The similarity of the waveforms demonstrates clearly that the correction of the short-period stations was successful. Slight

mismatches can be accounted for due to horizontal heterogeneities of the structure and/or the influence of the radiation pattern due to the difference in station azimuth of 9°.

Time windows used for inversion are set manually. For the broadband data, they are set around the entire seismogram; that is, the window starts before the *P* onset and ends after the dominant surface waves. Only if noise within the considered frequency range is obscuring the data, the time windows are set more strictly around the most energetic part of the observed signal. This is more often the case for horizontal components than for vertical ones. The maximum frequency range used for inversion on the broadband data is 0.02–0.1 Hz, which corresponds to surface waves. Depending on data quality and magnitude, this range differs slightly from event to event.

The short-period data are mainly inverted in the range of 0.2–0.5 Hz. For these frequencies, the appropriateness of the velocity model used starts to become critical, because of the relationship between frequency and wavelength. In a former study, we derived a 1D velocity model for moment tensor inversions within the Alborz mountains (Table 1; Donner *et al.*, 2013). This model proved to be quite satisfactory for mid- and long-period waveforms (10–60 s $\approx$ 0.016–0.1 Hz), while remaining reliable for frequencies up to about 0.3–0.5 Hz for body waves. It also maintains the time difference between *P* and *S* onsets very well (e.g., Figs. 4j and 5j). However, we have not tested the model for higher frequencies, and therefore we hesitate to use frequencies above 0.5 Hz for inversion.

The short-period stations are more prone to noise within the considered frequency range, especially after the *S* wave, where there is distinct scatter observed. Therefore, the windows are set only around the body waves, that is, they start before the *P* onset and end directly after the *S* wave.

We invert amplitude spectra using the program *mtinvers* (Dahm *et al.*, 1999), which applies an iterative weighted least-square algorithm. The residual is formed as

$$\text{res} = \sum_{i=1}^N \sum_{j=1}^{L_i} \frac{[w_i(d_{ij} - s_{ij})]^2}{[w_i \times d_{ij}]^2}, \quad (1)$$

in which d is observed data and s is synthetic data, respectively; w_i is the weight of the i th trace, and N and L are the

Table 1
Seismic Velocity Model Used for Waveform Modeling

Top of Layer (km)	V_P (km/s)	V_S (km/s)	V_P/V_S Ratio	Density (g/cm ³)	Q_P	Q_S
0	4.60	2.69	1.71	2.41	580	300
3	5.40	3.16	1.71	2.58	580	300
8	5.94	3.29	1.81	2.69	580	300
14	6.33	3.49	1.81	2.80	580	300
18	6.53	3.57	1.83	2.86	580	300
48	8.07	4.16	1.94	3.33	973	404
80	8.10	4.18	1.94	3.40	973	404

Properties are constant within individual layers. Q values are taken from Pasyanos *et al.* (2009a,b).

Figure 4. Inversion results for the earthquake on 05 June 2004 at 20:58 UTC from broadband data alone (a–f) and from combined broadband and short-period data (g–l). (a) and (g) show the event parameters and the solution together with first-motion body-wave polarities. Triangles and circles mark dilatational and compressional polarities, respectively. Crosses mark undefined polarities. (b) and (h) give inversion parameters assuming different depths. The three normalized, validated quantities residual (dashed lines), DC (dashed-dotted lines), and nonmatching polarities (dots) are plotted separately and as combination of the L2 norm (solid). (c) and (i) show the amplitude spectra from inversion, whereas (d) and (j) show the corresponding waveforms. Gray and black are observed and synthetic data, respectively. Numbers give the distance for each station in km. (e) and (k) show the distribution of stations used for inversion. (f) and (l) give the results of the jackknife tests showing all their solutions, the parameters of the tests, and a histogram of the Kagan rotation angles from all jackknife solutions compared to the initial solution.

Figure 5. Inversion results for the earthquake on 05 June 2004 at 22:12 UTC from broadband data alone (a–f) and from combined broadband and short-period data (g–l). Same as in Figure 4. The mechanism shown by the dashed line in (l) is representative for solutions with Kagan rotation angles of around 35°.

numbers and samples of traces, respectively. The weight w_i is set proportional to the square root of the distance between the analyzed earthquake and the recording station. For further details on the inversion algorithm, we refer to [Dahm et al. \(1999\)](#). We invert for only the deviatoric moment tensors because we are working on tectonic events and thus do not expect larger non-double-couple components.

Because the inversion is sensitive to centroid depth, we consider depths in a range between 2 and 40 km in increments of 2 km. To find the most reliable solution out of all possible solutions from the inversion, we not only rely on the lowest residual, but also consider a high percentage of the double-couple (DC) part (because we are considering tectonic events) and the lowest number of nonfitting first-motion body-wave polarities. These three criteria are combined by the L2 norm

$$\text{err} = \sqrt{\frac{\text{res}}{\text{res}_{\max}} + \left(1 - \frac{\text{DC}}{100}\right)^2 + \left(\frac{N_{\text{wrong}}}{N}\right)^2}, \quad (2)$$

in which res and $\text{res}_{\max}$ are the residual of the selected solution and the maximum residual over all depths, respectively. N and N_{wrong} are the numbers of available and nonmatching polarities, respectively.

It should be kept in mind that larger non-DC components of the solution might not only be an effect of a non-tectonic characteristic of the event, but also of mislocations of the hypocenter, mismodeling of the Green's functions (as discussed earlier), the methodical approach, or noise in the data, for example, due to a low SNR for a small magnitude event (e.g., [Adamová and Šílený, 2010](#); [Bukchin et al., 2010](#)).

To adapt the range of the three entities, we normalized them between zero and one. The residual was normalized by the maximum residual of the inversion. The number of nonfitting polarities was normalized by the maximum number of available polarities and the DC percentage was divided by 100. The solution whose depth has the lowest combined error (equation 2) is considered to be the most reliable one.

In a previous study ([Donner et al., 2013](#)), we estimated the error in depths by considering all depths within a range of the lowest selection criteria plus 20%. This was an *ad hoc* assumption based on practical considerations. [Valentine and Trampert \(2012\)](#) proposed the same general approach and assessed its applicability by mapping out the misfit function through forward modeling. They suggest a threshold of 10%, stating that this is a rather pessimistic assumption and showing that in some cases even a threshold of 1% or 5% is applicable as well. To determine the best threshold here is beyond the scope of this study. Therefore, we apply a threshold of 10% to give an estimate for the error in depth.

Equation (2) is not only used to select the most reliable centroid depth, but also to select the most reliable solution out of all possible solutions from inversion for a single depth. Particularly, the first-motion body-wave polarities give a strong constraint on the focal mechanism, whereas the

residual and DC part of equation (2) have a stronger influence on the depth selection. Thus, it is very easy to choose among competing solutions, as both explain the waveforms equally well (e.g., Fig. 4a,f).

To assess the stability of the solutions, we performed jackknife tests by randomly removing about 15%–20% of the complete traces covering all possible permutations of trace combinations. The stability of the solutions was then assessed by Kagan rotation angles ([Kagan, 1991](#)). A Kagan rotation angle is the minimum angle needed to rotate one moment tensor solution into another one in the 3D space. Rotation angles of less than 10° indicate stable solutions ([Kagan, 1991](#)).

Results

During inversion for moment tensors within the Alborz mountains, a minimum azimuthal gap of at least 120° is unavoidable due to the location along the coast of the SCB. When the inversion is restricted to broadband data, this gap is much larger (>250°), because there are no broadband stations in the eastern part of the Alborz mountains. Using broadband and short-period data, the azimuthal gap can be decreased significantly, depending on the earthquake location and which short-period stations are available. In general, the stability, and therefore the reliability of the solutions, can be improved. The error estimates for the depth could be reduced by about 2–6 km for the smallest events. The jackknife tests always demonstrated the improved stability of the solutions: from broadband data alone, none of the analyzed earthquakes showed averaged Kagan rotation angles of less than 10°. Inverting both kinds of data always resulted in median Kagan rotation angles of less than 10° with mean angles being only slightly higher. It was even possible to discriminate between two competing solutions (Fig. 4).

The results are summarized in Table 2. In the following, we describe them in more detail for each of the five events analyzed.

Earthquake 05 June 2004 20:58 UTC

This earthquake is one of the smaller aftershocks of the Baladeh sequence in 2004, which we analyzed in an earlier publication from broadband data alone ([Donner et al., 2013](#)). It occurred at 20:58:13 UTC at 36.414° latitude and 51.430° longitude with a Nuttli magnitude M_N of 3.2 ([Nuttli, 1973](#), IRSC). According to [Tatar et al. \(2007\)](#), the hypocenter was located at 22 km depth. The corner frequency was 1–2 Hz.

Data from only five broadband stations at distances from 75 to 420 km were available (Fig. 4e). Mainly vertical components were used for inversion, including eight traces all together. The azimuthal gap reached 260°. The deviatoric moment tensor has a DC of 81% and a residual of 0.087 (Fig. 4a). The inversion resulted in an oblique thrust mechanism with a seismic moment of 1.64×10^{14} N·m, corresponding to a moment magnitude of 3.4. The fit between

Table 2
Moment Tensor Results from Inversion of Only Broadband (Upper Line) and Combined Broadband and Short-Period Data (Lower Line)

Date (yyyy/mm/dd)	Time (UTC)	Latitude (°)	Longitude (°)	f_c^* (Hz)	$h^{\dagger}$ (km)	h Range ‡ (km)	M_0 (N·m)	M_w	m_{11}	m_{12}	m_{22}	m_{13}	m_{23}	m_{33}	$\phi^{\S}$ (°)	$\delta^{\P}$ (°)	$\lambda^{\#}$ (°)	DC (%)	CLVD (%)	α^{**} (°)	res
2004/06/05	20:58:12	36.414	51.430	2.0	26	16–30	1.64×10^{14}	3.4	−0.60	−0.10	0.23	−0.70	−0.48	0.36	64	23	33	81	−19	31	0.087
2004/06/05	20:58:12	36.414	51.430	2.0	26	26–28	1.67×10^{14}	3.4	−0.73	−0.10	0.27	−0.48	−0.60	0.46	65	33	30	92	8	5	0.153
2004/06/05	22:12:45	36.443	51.520	2.0	20	18–22	5.96×10^{13}	3.1	−0.16	−0.29	−0.45	−0.46	−0.64	0.61	151	19	96	96	−4	61	0.032
2004/06/05	22:12:45	36.443	51.520	2.0	24	24–26	7.64×10^{13}	3.2	−0.02	0.08	−0.60	−0.32	−0.72	0.62	203	23	127	79	21	7	0.107
2004/02/21	12:07:03	35.740	52.270	2.0	14	14–16	1.02×10^{15}	3.9	0.03	−0.36	−0.47	0.78	0.24	0.44	118	76	65	84	16	7	0.107
2004/09/24	01:42:48	35.678	52.405	1.5	4	4–6	1.87×10^{15}	4.1	0.30	−0.84	−0.16	0.25	0.41	−0.14	274	68	−18	79	−21	9	0.082
2004/09/24	01:42:48	35.678	52.405	1.5	6	6–8	1.70×10^{15}	4.1	0.37	−0.80	−0.15	0.15	0.27	−0.22	276	73	−15	83	17	8	0.107
2006/12/20	04:39:20	35.802	51.915	2.0	14	14–14	5.57×10^{14}	3.8	−0.28	−0.89	0.09	0.33	−0.19	0.19	89	78	22	91	−9	75	0.056
2006/12/20	04:39:20	35.802	51.915	2.0	16	14–18	2.58×10^{14}	3.6	−0.72	−0.17	0.93	0.45	0.24	−0.21	227	61	−16	93	−7	3	0.199

For the event on 21 February 2004, no broadband data are available.

* f_c is the corner frequency of the earthquake.

$^{\dagger}h$ is the obtained centroid depth.

$^{\ddagger}h$ range is the error estimate for the depth.

$^{\S}\phi$ is the strike angle.

$^{\P}\delta$ is the dip angle.

$^{\#}\lambda$ is the Rake angle.

** α gives the median Kagan rotation angle (Kagan, 1991) of all jackknife solutions and is a measure for solution stability. Angles below 10° indicate a stable solution.

observed and synthetic amplitude spectra is good, except for the vertical component of station NASN (Fig. 4c). All stations show a good match between observed and predicted waveforms (Fig. 4d). The resulting centroid depth of 26 km showed a large uncertainty, and depths between 16 and 30 km are within the 10% misfit threshold (Fig. 4b). The jackknife test (2 out of 8 traces, i.e., 25% and 28 permutations) on the inversion of amplitude spectra showed a maximum Kagan rotation angle of 80° with mean and median angles of 38° and 31°, respectively (Fig. 4f). All six components of the moment tensor showed strong scatter in their distribution after the jackknife test. The large maximum Kagan rotation angle corresponds to a competing solution, in which the northeast–southwest oriented plane dips to the northwest instead of to the southeast. This competing solution can be excluded from the distribution of the first-motion polarities on the solution.

Six short-period stations show data of sufficient quality to use their waveforms for inversion for moment tensors, adding 13 traces (Fig. 4k). They are mainly located to the south and east of the event, thus decreasing the azimuthal gap to 200°. From broadband and short-period data together, the deviatoric moment tensor clearly results in an oblique thrust mechanism with the strike-slip component to the southeast, which is slightly rotated compared to the broadband solution. The residual is 0.153 and the seismic moment is 1.67×10^{14} N·m, corresponding to M_w 3.4. The DC is 92% of the seismic moment (Fig. 4g). The fits of synthetic and observed amplitude spectra and waveforms show more weaknesses than the ones from the broadband data alone but are still a good match (Fig. 4i,j). The inversion assuming different source depths gives a depth of 26 km with depths between 26 and 28 km falling within the 10% misfit threshold (Fig. 4h). The depth is much better constrained than that for the broadband solution. For the jackknife test on amplitude spectra, 3 out of 21 traces were removed (i.e., 14% and 1330 permutations; Fig. 4l). The result is much more stable than for broadband data alone, with 76% of the solutions having Kagan rotation angles of less than 10°. The maximum, mean, and median rotation angles are 87°, 11°, and 5°, respectively. The competing solution vanished almost completely. Only 7% of all jackknife solutions still show the competing solution.

Earthquake 05 June 2004 22:12 UTC

This earthquake is the smallest of the aftershocks of the Baladeh sequence in 2004, which we studied in an earlier publication from broadband data alone (Donner *et al.*, 2013). It occurred at 22:12:45 UTC at 36.443° latitude and 51.520° longitude with a Nuttli magnitude of M_N 3.3. According to Tatar *et al.* (2007), the hypocenter is located at 22 km depth. We determined the corner frequency to be about 2 Hz.

Four broadband stations, with six traces in total, provided usable data for inversion, leading to an azimuthal gap of 290° (Fig. 5e). The inversion resulted in a thrust

mechanism on northwest–southeast oriented planes with a residual of 0.032 and a DC percentage of 96%. The seismic moment was determined to be 5.96×10^{13} N·m, corresponding to a moment magnitude of 3.1. The fit of the amplitude spectra is good for the vertical components and still acceptable for the two horizontal components (Fig. 5c). The fit of the predicted and observed waveforms is almost perfect, even for the horizontal components (Fig. 5d). Station SNGE is the only exception. Here, the data are spoiled by noise. Nevertheless, the fit is still good within the time window used. The centroid depth was determined to 20 km but could also be set between 18 and 22 km (Fig. 5b). For the jackknife test on amplitude spectra, one out of six traces were removed (i.e., 17% and 6 permutations; Fig. 5f). The maximum, mean, and median Kagan rotation angles are 93°, 53°, and 61°. Although the fit between observed and synthetic amplitude spectra and waveforms is good, the solution for this event was considered to not be reliable enough for tectonic interpretation in the previous publication (Donner *et al.*, 2013).

Seven short-period stations contributed 13 traces to the inversion (Fig. 5k). Thus, the azimuthal gap was reduced to 210°. The solution was rotated to more north–south oriented planes (Fig. 5g). The inversion for the deviatoric moment tensor ended in a residual of 0.107 and a seismic moment of 7.64×10^{13} N·m, corresponding to M_w 3.2. The DC part contains 79% of the moment. The fit of the amplitude spectra show some weaknesses, especially on the horizontal components, but is still good (Fig. 5i). The fit of predicted and observed waveforms is also generally good but includes minor time shifts between data and synthetics (Fig. 5j). Furthermore, the maximum amplitudes do not always match. We refer the weaknesses between observed and synthetic spectra and waveforms to the low magnitude of the event and the resulting decreased SNR.

The centroid depth was determined to be 24 km, with 24–26 km being within the 10% error threshold (Fig. 5h). For the jackknife test, 3 out of 19 traces (i.e., 16%, 969 permutations) were removed. The minimum, maximum, mean, and median Kagan rotation angles are 0°, 82°, 16°, and 7°, respectively. 61% of the solutions have Kagan rotation angles of less than 10°. Another 13% have angles around 35°–40°. These angles belong to a competing solution also shown in Figure 5l (dashed line). This solution, however, is still a thrust mechanism on north–south oriented planes. The possible strike-slip mechanism from the jackknife test of broadband data alone vanished completely. The larger Kagan rotation angles result from a larger scatter of strike, dip, and rake angles.

Earthquake 21 February 2004 12:07 UTC

This earthquake was located at 35.740° latitude and 52.273° longitude in close vicinity of the Mosha Fasham fault in the south-central Alborz mountains. There is no good control on the hypocenter depth due to a lack of data from very close stations. The Nuttli magnitude is determined to

M_N 4.4. The corner frequency of this earthquake is about 2 Hz.

Because of its early date, no broadband data are available for this event, but five short-period stations recorded good quality data and 13 traces could be used for inversion (Fig. 6e). The azimuthal gap is 120°. The inversion for the deviatoric moment tensor resulted in an oblique thrust mechanism on northwest–southeast oriented nodal planes (Fig. 6a). The centroid depth was very clearly determined to be 14 km with a range of 14–16 km within the 10% threshold (Fig. 6b). It is the distinct curve of the residual that bounds the depth so tightly. The solution has a residual of 0.107 and a seismic moment of 1.02×10^{15} N·m, corresponding to a moment magnitude of 3.9. The DC part contains 84% of the moment. From the fit of the first-motion polarities, the solution might be slightly rotated. The amplitude spectra show a good fit, although the inversion is not supported by broadband waveforms (Fig. 6c). Also, the predicted and observed waveforms match very well within the time windows used, although at some stations time shifts are recognizable (Fig. 6d). The vertical component of station DMV shows reversed polarities. This is explained by the close vicinity of this polarity to a nodal plane. The slight rotation mentioned above would also resolve this problem. For the jackknife test, we removed 2 out of 13 traces (i.e., 15%, 78 permutations, Fig. 6g). The solution is remarkably well resolved. The maximum, mean, and median Kagan rotation angles are 90°, 32°, and 7°, respectively. 60% of all solutions have rotation angles less than 10°.

Earthquake 24 September 2004 01:42 UTC

Located close to the Mosha Fasham fault, the coordinates of this event are 35.678° latitude and 52.405° longitude. It occurred at 01:42:48 UTC with a Nuttli magnitude of M_N 3.9. Like the previous earthquake analyzed, there is no good control on the hypocenter depth. We determined the corner frequency to about 1.5 Hz.

Four broadband stations provided usable data for inversion (Fig. 7e). Just one of these stations is within a distance of 40 km, whereas the others are 530–1030 km away to either the northwest or southeast. The azimuthal gap is 185°. We obtained a pure strike-slip mechanism on northwest–southeast and northeast–southwest oriented planes with a seismic moment of 1.87×10^{15} N·m, corresponding to M_w 4.1 (Fig. 7a). The centroid depth is very shallow at 4 km. The 10% error threshold gives a depth range of 4–6 km.

The residual for the solution is 0.082 with a DC part of 79%. The fit of the amplitude spectra is generally good (Fig. 7c). Stronger discrepancies are recognizable for the stations ZHSF and GHIR. Nevertheless, for all stations the match between predicted and observed waveforms is very good (Fig. 7d). At station ZHSF (distance: 1032 km) a time shift of about 10 s is observed between predicted and observed waveforms, which is related to a Global Positioning System timing problem during that time (Donner

Figure 6. Inversion results for the earthquake on 21 February 2004 at 12:07 UTC from short-period data alone. No broadband data are available for this earthquake. Same as in Figure 4.

et al., 2013). We have shifted the observed and theoretical traces for inversion and plotting accordingly. For the jackknife test, we removed 1 out of 8 traces (i.e., 13%, 8 permutations; Fig. 7f). It clearly shows two ambiguous solutions. The maximum, mean, and median Kagan rotation angles are 47°, 19°, and 9°, respectively.

Six short-period stations provided additional data. The newly obtained solution has a residual of 0.169 and a seismic moment of 1.64×10^{15} N-m, corresponding to an M_w 4.1 (Fig. 7g). The mechanism has the same strike-slip character as the pure broadband solution with almost the same DC part of 80%. The depth is again 4 km (Fig. 7h). Still, the depth resolution is crude with almost flat curves from 8 km depth onwards. The fit of the amplitude spectra is good (Fig. 7i), although the comparison of observed and predicted waveforms shows strong noise within the frequency band used (Fig. 7j). Nevertheless, within the time windows used the waveform fit is good.

For the jackknife test, 3 out of 21 traces were removed (14%, 1330 permutations). The solution turned out to be stable in its strike-slip character and its strike angles. However, the dip angles for both nodal planes show stronger scatter, which also leads to higher rotation angles. The maximum, mean, and median Kagan rotation angles are 99°, 40°, and 8°. 49% of the 1330 permutations have Kagan rotation angles

of less than 10°. 33% of the solutions have Kagan rotation angles between 85° and 95°. They belong to the same solution, with a right-lateral instead of left-lateral character. This ambiguity is inherited from the method of inverting amplitude spectra, which cannot distinguish between quadrants of compression and dilatation. Therefore, the large Kagan rotation angles do not indicate an unstable solution here. The ambiguous solution having Kagan rotation angles of about 70° is also still visible. However, it only accounts for 5% of the solutions and is therefore neglected.

Earthquake 20 December 2006 04:39 UTC

This event also occurred in close vicinity of the Mosha Fasham fault, if not directly on the fault. Latitude and longitude are 35.802° and 51.915°, respectively (Fig. 8e,k). The hypocenter depth is determined to be 14 km with an error of 5 km and the corner frequency is about 2 Hz.

Data from only three broadband stations (4 traces) could be used for waveform inversion (Fig. 8e). This leads to an azimuthal gap of 245°. We obtained a strike-slip mechanism on north-south and east-west oriented planes with a seismic moment M_0 of 5.57×10^{14} N-m, corresponding to a moment magnitude of M_w 3.8 (Fig. 8a). The residual is 0.056 with a DC percentage of 91%. The observed and synthetic amplitude spectra fit well (Fig. 6c). Also the observed and

Figure 7. Inversion results for the earthquake on 24 September 2004 at 01:42 UTC from broadband data alone (a–f) and from combined broadband and short-period data (g–l). Same as in Figure 4.

Figure 8. Inversion results for the earthquake on 20 December 2006 at 04:39 UTC from broadband data alone (a–f) and from combined broadband and short-period data (g–l). Same as in Figure 4.

predicted waveforms match well. We determined a centroid depth of 14 km. Although the curve of the lowest residual is flat between 8 and 16 km, no depths other than 14 km fall

within the 10% threshold (Fig. 8b). The number of non-matching polarities and the distinct curve for the DC part keep the depth fixed. As expected, the jackknife test (1 out

of 4 traces, i.e., 25% and 4 permutations) showed strong scatter with maximum, mean, and median Kagan rotation angles of 95°, 64°, and 75°.

Data from seven short-period stations (14 traces) could additionally be used for inversion, decreasing the azimuthal gap considerably to 170° (Fig. 8k). The retrieved solution is still a pure strike-slip mechanism but on northwest–southeast and northeast–southwest striking nodal planes. It has a residual of 0.199 and a seismic moment of 2.58×10^{14} N·m, corresponding to M_w 3.6 (Fig. 8g). This mechanism better explains the observed first-motion body-wave polarities. The number of nonfitting polarities decreased from five (broadband solution) to two. One of them is very close to a nodal plane and thus may be related to ray-path effects. Yet, the seismic moment is much smaller, leading to a decrease of the moment magnitude of 0.2. The fit of the amplitude spectra is good in general, with some weaknesses on the horizontal components (Fig. 8i). The predicted and observed waveforms fit well within the time window used, except there are slight time shifts visible on some stations, for example, station LAS. The centroid depth now shifts to 16 km and is better constrained (Fig. 8h). Depths of 12 and 18 km are within the range of the 10% error threshold. During the jackknife test, 2 out of 18 traces were removed (i.e., 11%, 153 permutations; Fig. 8l). It is much more stable than for the broadband data alone. However, the test reveals a competing solution. It is a thrust mechanism on northwest–southeast oriented planes. Such a solution would contradict the distribution of first-motion body-wave polarities completely. The maximum, mean, and median Kagan rotation angles are 84°, 11°, and 3°, respectively. 86% of all solutions have Kagan rotation angles of less than 10%. Therefore, the competing thrust solution, accounting for only 9% of all solutions, is negligible.

Discussion

Inversion for moment tensors in the Alborz mountains is hampered due to several reasons. The localization of the mountain range along the shore line of the SCB leads to large azimuthal gaps (Fig. 1). They are enlarged due to a heterogeneous network of broadband stations. Especially for the year 2004 (initial establishment of the network), data availability from this network is sparse. In addition, strain in the Alborz mountains is released by rare strong earthquakes (Zamani and Agh-Atabai, 2009). Therefore, only a few events per year are strong enough to be processed with standard methods and from broadband data alone.

We successfully corrected short-period waveform data for the instrument response and can thus include them in the inversion for moment tensors. The correction of the data is stable down to 0.1 Hz. Below this value, high-frequency noise is amplified strongly by the instrument correction. Thus, we are restricted to body waves during inversion of short-period waveforms. The azimuthal gaps could be decreased significantly, although they are still large.

Šílený (2004) found the full moment tensor is resolved well within a passband of 25–50 s for a model uncertainty of up to 30% and within 10–25 s for an uncertainty up to 10%. The moment tensor was undetermined for periods of 5–10 s. However, Šílený *et al.* (1992) showed the mechanism still can be derived well when inverting only for the deviatoric moment tensor. Nevertheless, we performed an additional test to see whether the inversion of short-period data in the high-frequency range (i.e., periods of 2–5 s) is stable. The assumed velocity model, which we derived in an earlier publication (Donner *et al.*, 2013), has a formal standard error of 0.02 km/s. We tested the solution of the event on 05 June 2004 at 20:58 against overall perturbations of ± 0.02 km/s, ± 0.04 km/s, and ± 0.1 km/s within the top 18 km of the model. We found a very stable solution for all perturbations. The Kagan rotation angles compared to the solution using the initial model are always less than 10° or only slightly above.

With the approach presented in this paper, it was possible to distinguish between competing solutions, where the nodal planes dip in opposite directions, and both are explained equally well by the broadband waveforms alone (Fig. 4f,l). The distribution of first-motion body-wave polarities and a combined L2-norm error from the inversion residual, the DC part, and the nonmatching polarities (equation 2) are also a great help in such cases. It helps to identify the most reliable of all possible solutions from the inversion when the strike and dip angles of the resulting solution show slight scatter (e.g., Fig. 6l). Moreover, the criterion in equation (2) helps to prevent the selection of a wrong depth. Selecting a depth according to only the lowest residual might lead to a solution that has a low DC part, which is atypical for tectonic events, and, in the worst case, is not explained by the first-motion body-wave polarities.

We managed to obtain a reliable solution for an earthquake as small as M_w 3.1 on the regional scale. This earthquake, however, also exposes the limits of our approach. A low SNR due to the small magnitude and high noise within the inverted frequency range complicated the inversion. The quality of the velocity model also influences the lower magnitude threshold for applying our approach. Because we do not know exactly how well our velocity model performs for frequencies above 0.5 Hz, we have to restrict the inversion to frequencies below this value. We anticipate that our method will not be successful for events with magnitudes below M_w 3.0, at least not under the conditions within the Alborz mountains. In other regions with better data quality, a well constrained structural model, and/or better station coverage, it might be possible to decrease this magnitude threshold. The benefit of the approach for the Alborz mountains is still significant. Between 1997 and 2012, only 120 earthquakes with magnitudes of M_L 4.0 occurred, of which only 40 events had magnitudes above M_L 4.5. That is 8 and 3 events per year, respectively. These events could be processed with standard inversion methods and from broadband data alone, but for comprehensive seismotectonic studies, this number is

Figure 9. (a) The Tehran region, showing earthquakes related to the Moshafasham fault. Black and gray focal mechanisms are seismic moment tensors retrieved in this study (since 2004) and listed by the Global CMT project (since 1976), respectively. Numbers above the mechanisms give the date of the event (yy/mm/dd). Open circles mark the seismicity with $M_N \geq 2.5$ between 2004 and 2012, according to the IRSC. Depths of this catalog contain large uncertainties (Ghods and Sobouti, 2005). (b) Depth profile perpendicular to the Moshafasham fault. Seismicity and mechanisms follow those in (a). The position of the Moshafasham fault along the profile is marked by a reversed triangle.

too low. Within the same time period, 975 earthquakes with magnitudes $3.0 \leq M_L \leq 4.0$ occurred, of which 242 had magnitudes above M_L 3.5. That is 65 and 16 events per year, respectively. With our approach, it would be possible to process these events as well, providing a sufficiently large database for seismotectonic studies.

There is also an upper magnitude threshold for applying our approach. The larger the event, the smaller the corner frequency of the radiated waves, and therefore the lower the frequencies have to be for inversion to ensure the validity of the point-source assumption. The lower the inverted frequencies are, the less applicable is the use of short-period stations, because they no longer record these frequencies, at least not proportional to the ground motion. With a successful instrument correction, we can decrease the minimum frequency to the point where we can use the short-period data; in our case, down to about 0.1 Hz. For all earthquakes with much larger corner frequencies, the short-period data can theoretically be used for waveform inversion, depending on the appropriateness of the velocity model. This lower frequency limit, according to established scaling relations, is congruent to a magnitude of about M_w 4.5 depending on the stress drop of the event and the S -wave velocity at the source (e.g., Havskov and Ottemöller, 2010). In this study, the larg-

est magnitude to which the approach was applied is M_w 4.1 (Fig. 7a–l). The inversion of combined data stabilized the solution. The depth resolution decreased when combining both data, although it was also not good from broadband data alone. This poor result might either be an effect of the inappropriate distribution of the broadband stations (one very close, the rest very far), or it is an indication of the upper magnitude limit for using short-period data. For other earthquakes we analyzed, the depth resolution did increase (Fig. 4b,h).

In summary, the corner frequency of the event has to be checked carefully for all earthquakes with magnitudes $M_w \geq 4.0$ before using short-period data for inversion.

Three of the earthquakes analyzed in this study occurred in close vicinity to the Moshafasham fault (Fig. 9). The Moshafasham fault is well studied by microseismic, paleoseismic, and morphotectonic surveys (Ashtari et al., 2005; Ritz et al., 2006; Landgraf et al., 2009; Tatar et al., 2012). The kinematics of the Moshafasham fault is linked with the north Tehran thrust fault further west. Both faults developed as a right-lateral strike-slip system, caused by northwest oriented shortening in earlier times, before their kinematics changed to left-lateral due to a rotation of the compressional direction to northeast at about 5 Ma. Recently, a transtensional component seems to be evident (Ritz et al., 2006; Landgraf et al., 2009).

Microseismic studies exposed a stronger seismicity for the central-eastern part of the fault (about longitude 52°), at least in modern times, and a northward dip of about 70° (Ashtari et al., 2005; Tatar et al., 2012). According to Tatar et al. (2012), focal mechanisms from first-motion body-wave polarities separate in shallower left-lateral strike-slip and deeper thrust mechanisms. The mechanisms located between the Moshafasham fault and the Firuzkuh fault located farther south mainly show normal motion but also include thrust and strike-slip mechanisms. Interestingly, they found an $\sim 40^\circ$ south-southwest-dipping structure, which would project very close if not exactly to the Moshafasham trace at the surface at the central-eastern part of the region. Directly east of that structure (about longitude 52.2°), a distinct cluster of seismicity in the deeper footwall of the Moshafasham fault is also visible. There, the earthquakes show mainly thrust mechanisms.

From the three earthquakes ($3.6 \leq M_w \leq 4.1$) in that region analyzed in this study, we can see that all mechanisms are located at depths of 5–15 km. The most eastern earthquake is a pure left-lateral strike-slip on east–west and south–north oriented nodal planes, whereas the middle one at 52.27° longitude shows an oblique thrust mechanism. The westernmost earthquake shows an almost pure strike-slip mechanism on nodal planes rotated to northwest–southeast and northeast–southwest. Except for the easternmost mechanism, the earthquakes dip to the north with dip angles varying between $\sim 70^\circ$ and $\sim 85^\circ$. However, the steep dip angles make it difficult to distinguish between a dip to the north and south from the waveform inversion. It might be

that the easternmost earthquake also dips to the north (Fig. 7).

The westernmost earthquake of the three is intriguing. Considering the northwest–southeast nodal plane, which would fit the strike of the Mosha Fasham fault best but still includes an angle of about 30° to the trend of the fault, it has a right-lateral character. That movement contradicts the left-lateral kinematics of the fault. A better match considering both the strike and kinematics would be the North Tehran thrust. More moment tensors for smaller earthquakes in that region could strongly contribute to the understanding of the activity and interaction of the faults in this very important and complex fault system.

Conclusion

In this study, we demonstrated the applicability of integrating short-period waveform data into inversion for regional moment tensors for small to moderate sized earthquakes on a regional scale. The success of our approach mainly depends on the appropriate instrument correction of the short-period waveforms and the availability of a suitable velocity model, which models the shape of not only mid- to long-period waveforms (surface waves), but also waveforms of higher frequencies (body waves).

By combining broadband and short-period waveform data for inversion, we obtain stable and reliable results, even for events in which the inversion of broadband data alone fails. Along with the mechanisms, the seismic moments and centroid depths are also well resolved. This novel approach allows a reduction in the lower magnitude threshold for which waveform inversion is possible. Within the Alborz mountains, Iran, we expect this threshold to be about M_w 3.0. The threshold may be even lower for other regions of the world. Thus, many more earthquakes can be processed to obtain a comprehensive database of moment tensors for seismotectonic interpretations.

With the approach presented here, it is possible to successfully retrieve moment tensors in regions where a sparse broadband station network, unfavorable station distribution, low-data quality, and/or the absence of moderate to large magnitude earthquakes have so far prevented the application of standard inversion methods.

Data and Resources

Waveform data are provided by the International Institute of Earthquake Engineering and Seismology and the Iranian Seismic Center of the Institute of Geophysics, Tehran University. Catalog information of background seismicity was searched using www.iiies.ac.ir/iiies/English/index_e.asp and irsc.ut.ac.ir (last accessed August 2013). The Global Centroid Moment Tensor Project database was searched using www.globalcmt.org/CMTsearch.html (last accessed August 2013).

Data processing was carried out with the help of Seismic Handler by Klaus Stammer and Marcus Walther (www.seismic-handler.org; last accessed August 2013). All figures were created using the Generic Mapping Tool by Paul Wessel and Walter H. F. Smith (gmt.soest.hawaii.edu/; last accessed August 2013).

Acknowledgments

This study was funded by the German Research Council (DFG Project KR 1935/12-1) and funds from the DFG Leibniz Award to M. Strecker (DFG project STR 373/20-1). We greatly appreciate the data supplied by the Iranian Institute of Earthquake Engineering and Seismology (IIIES) and the Institute of Geophysics, University of Tehran (IGUT). This study benefited from discussions with Paolo Ballato, Angela Landgraf, and Carsten Riggelsen. We acknowledge Associate Editors Heather DeShon and John Ristau and an anonymous reviewer for their useful comments. We thank A. Popiel and T. Schildgen for their editorial work.

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Manuscript received 25 August 2013;
Published Online 15 April 2014