IMPROVED ESTIMATION OF SEISMIC FOCAL DEPTHS IN IRAN

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ABSTRACT

Accurate estimates of seismic focal depth and mechanism are important for event identification and empirical calibration of regions of monitoring concern. We have used 1-D raytracing of teleseismic body waves to estimate hypocentral depths of recent, moderate-size earthquakes in Iran. The waveform modeling involves matching the shape and amplitude of the direct P and SH arrivals together with the pP, sP and sS surface-reflected phases. This form of waveform modeling can constrain the focal depth to within 2-5 km. Our results, and the results of several earlier studies of Iranian earthquakes using waveform modeling, show that most (94%) of the events in the magnitude range Mw 5.3 to 6.3 in the Zagros Mountains of Iran lie within the uppermost 20 km of the crust. Many of our well-constrained focal depths are significantly shallower than the focal depths for these events reported by Engdahl, van der Hilst, and Buland (1998). We are using the cepstral depth estimation procedure of Reiter and Shumway (1999) to provide an independent estimate of the focal depth these Iranian earthquake results. The cepstral analysis technique detects the delay times of pP-P and sP-P through straightforward signal-processing methods, and assigns statistical significance to the measured delays. Tests to date show that the cepstral method and the body waveform modeling results agree exceptionally well for these moderate size earthquakes. We are now extending our tests to smaller events that cannot be recorded teleseismically. We are using the waveform modeling results for the moderate size earthquakes to calibrate the propagation paths to digital seismographs located in the Caspian region north of Iran. We will then use these results to model the regional waveforms recorded at the Caspian stations for smaller events, and verify the depths of the smaller events using cepstral analysis.

Keywords: seismic focal depth, waveform modeling, cepstral analysis, Iran, Caspian Sea

OBJECTIVE

The primary objective of this research is to accurately determine the depths of small magnitude earthquakes in Iran from seismograms recorded at regional distances. To accomplish this we are using well-located, moderate-size earthquakes to calibrate regional seismic stations in the Middle East. The focus of our work to date has been on building a database of well-located events whose source parameters have been determined by teleseismic waveform modeling with an independent focal depth determination using the cepstral F-statistic method (Reiter and Shumway, 1999). Some of these events have additional source information from field studies. We use the results from the moderate-size earthquakes to calibrate the regional seismographs. Once calibrated, the cepstral depth estimation technique can be applied to regional seismograms to estimate focal depths of small magnitude events. This work will result in a database of well-located, moderate-size events in Iran, a catalogue of small magnitude Iranian events whose focal depths are accurately known, and a calibrated procedure for depth determination in the region. We feel that a combining teleseismic waveform modeling and the cepstral F-statistic method to estimate and validate our depth estimates can improve the regional calibration of events in Iran.

RESEARCH ACCOMPLISHED

Regional path calibration of seismic phases depends on the accuracy of hypocentral locations of seismic events. While moderate-size events present no challenge for seismic identification and discrimination, the study of the waveform characteristics of larger magnitude events can provide information necessary for regional path corrections that are important for the identification and discrimination of small magnitude events. We have used well-located, moderate-size events in Iran to calibrate regional seismic stations. We then use data from regional seismic stations to estimate focal depths of small magnitude events.

Waveform Analysis

We analyze P- and SH-waveforms taken from the Global Digital Seismic Network (GDSN) and GEOSCOPE stations to constrain the source parameters of moderate-size earthquakes in Iran. Source parameters are determined using McCaffrey and Abers' (1988) version of Nabelek's (1984) waveform inversion program. This method minimizes, in a least-squares sense, the misfit between the shape and amplitude of the observed and synthetic P- and SH-waveforms. The synthetic seismograms are computed for a point source embedded in a simplified Earth structure by combining the direct arrival (either P or S) with the near-source reflections (pP and sP, or sS) and near-source multiples. Amplitudes are corrected for geometrical spreading, and for anelastic attenuation using a Futterman Q operator with a t* value of 1.0 s for P and 4.0 s for SH waves. This procedure is now routine, and detailed descriptions can be found in McCaffrey and Abers (1988).

The inversion method minimizes the misfit between the observed and synthetic waveforms by varying the strike, dip, slip, centroid depth, seismic moment, and source time function. To avoid complications introduced by the upper mantle triplication or core phase interference, we restricted the body waveform inversion to P-waves in the 30^o to 90^o distance ranges and S-waves in the 35^o to 84^o distance range. Because of their large amplitudes, SH seismograms were given only 50% of the weight of the P-wave seismograms in the inversion process, and all seismograms were azimuthally weighted; that is, seismograms from stations clustered together in azimuth were given lower weight than seismograms from isolated stations. For these moderate size events we assumed that all slip occurs at the same point in space (centroid location), but the source time function is distributed in time. The source time function is described by a series of overlapping isosceles triangles (Nabelek, 1984).

A minimum misfit set of source parameters is found by the inversion routine. Priestley et al. (1994) have performed tests to evaluate the effects of the unknown velocity structure in the source region. They find that reasonable variations in crustal velocity structure do not result in significant changes in strike, dip, and rake, but can affect centroid depth, moment, and the source time function. Uncertainties in t* lead to uncertainties in source duration and seismic moment, but have only a small effect on centroid depth and source orientation. Uncertainties in the source parameters were estimated in two ways. First we computed the formal errors in these parameters in the inversion procedure, but our past experience has shown that these uncertainty estimates are overly optimistic. Consequently, we also performed a series of tests to assess more realistic uncertainties and examine trade-offs between the various parameters. Our test procedure is to fix the source parameter being examined at a series of values that bracket the minimum misfit value, then reinvert the waveform data to examine what effect variations in the fixed parameters have on the free parameters. We then visually inspected the fit of the observed and synthetic waveforms to see if there was any deterioration in the fit. We continued this procedure, adjusting the value of the free parameter away from the minimum misfit value until the fit between the observed and synthetic waveforms was noticeably worse, and thereby estimated a more realistic bound on that source parameter. Our tests showed that the strike, dip, rake, and centroid depth are relatively independent of each other. That is, when one parameter was held fixed at a value within a few degrees or kilometers of its minimum misfit value and the waveforms reinverted, the resulting values of the free parameters were close to their minimum misfit values. From these tests we estimate the uncertainty bounds on the centroid depth are ± 3 km, the strike ± 15°, the dip ± 4°, and the rake ± 20°. These uncertainties are of similar magnitude to those noted in comparable studies in other regions (e.g. Molnar and Lyon-Caen, 1989; Baker et al., 1993; Priestley et al., 1994).

We have modeled the waveform of the Zagros Mountains earthquake of July 31, 1994 in the Iran region (Figure 1). The results from the waveform analysis are shown in Figures 2 and 3. This moderate size (International Seismological Centre (ISC): m_b 5.2, M_S 5.3) earthquake occurred on July 31 1994 in the western Zagros Mountains (32.58 ± 0.027°N, 48.37 ± 0.020°E). The focal depth is given as 43 km by the National Earthquake Information Center (NEIC), 44 ± 2.4 km by the ISC and 45 km by Engdahl et al. (1998). We analyzed 22 P- and 18 SH- digital waveforms obtained from the GDSN and GEOSCOPE networks. Figure 2 shows the match between the observed seismograms and synthetic P and SH seismograms computed for the minimum misfit solution. The minimum misfit solution, a low angle thrust, is not typical for the Zagros Mountains, which mainly have high angle reverse or strike-slip mechanisms. The focal depth is 14 km and the source time function is a simple pulse with a total (95%) duration of 2.5s.

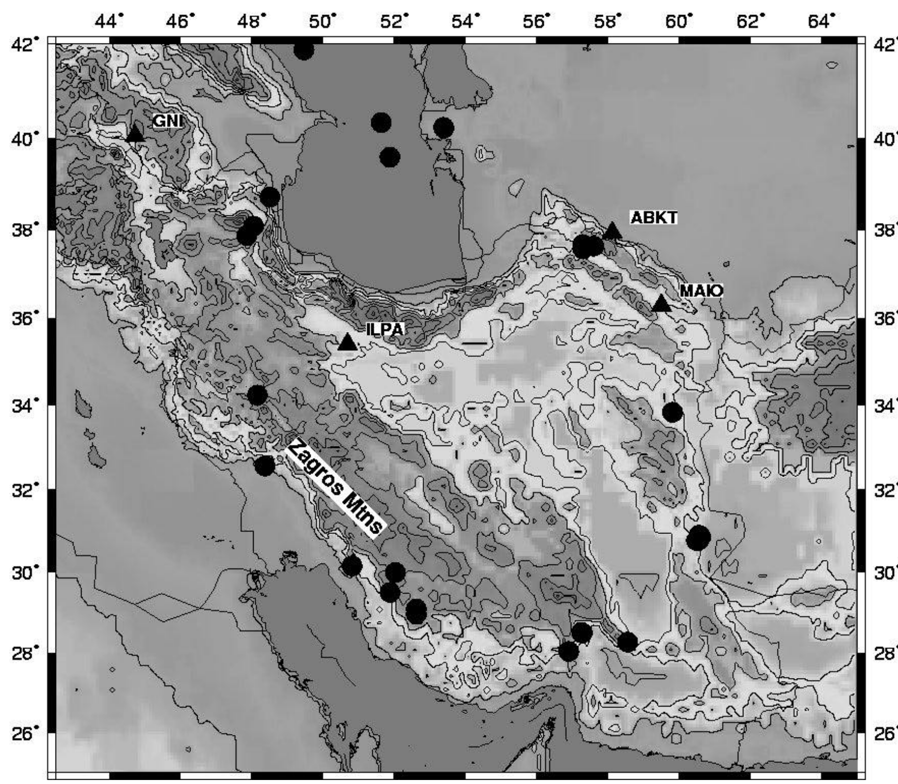

Figure 1. A topography map showing the area of study. The earthquakes under analysis for our study are represented by black dots, and nearby stations are denoted by triangles. The July 31, 1994 earthquake analyzed in the body of the paper is in the western Zagros Mountains (32.58 ± 0.027°N, 48.37 ± 0.020°E).

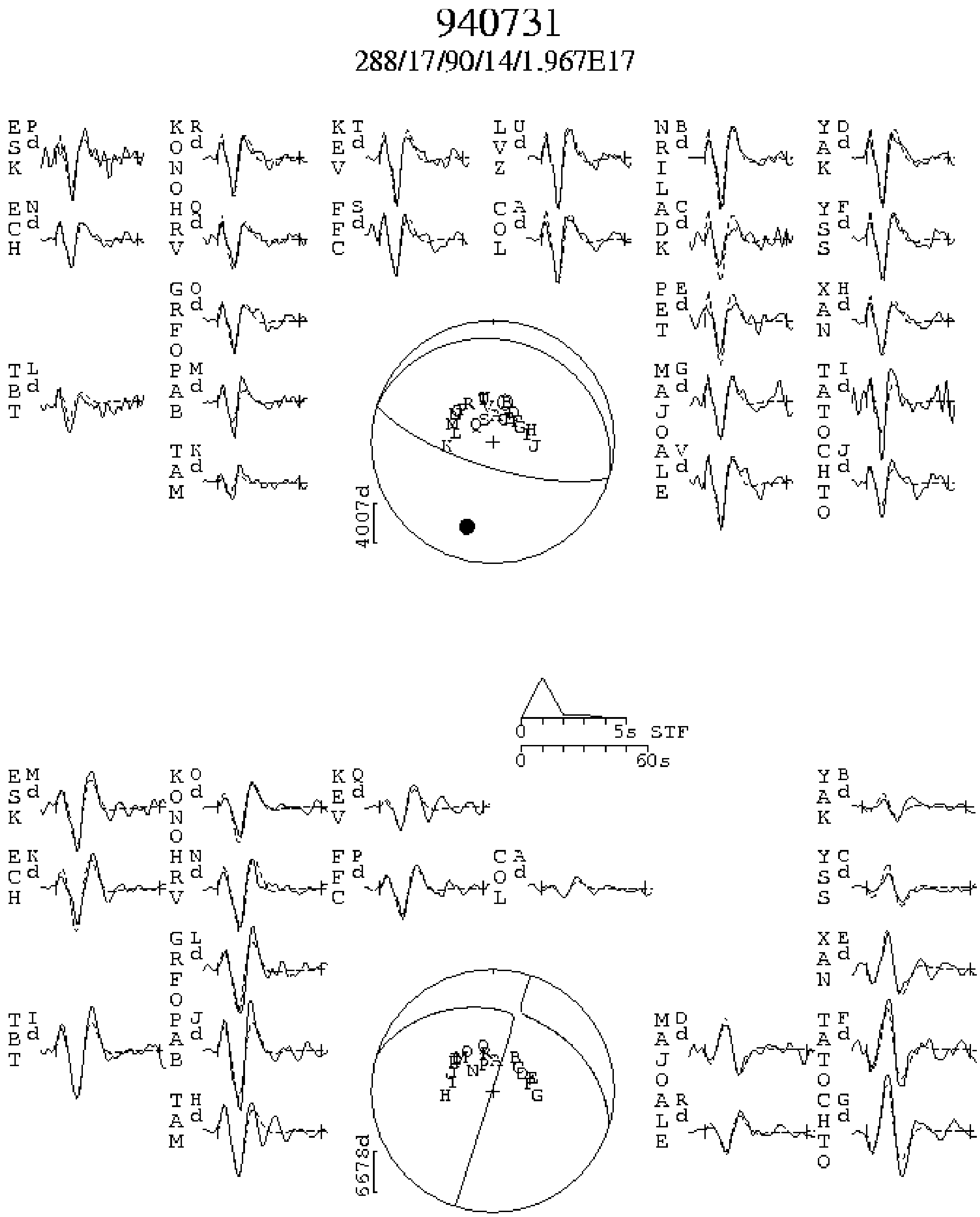

Figure 2. The P and SH radiation patterns of the minimum misfit solution for the Zagros Mountains earthquake of July 31, 1994. The values beneath the event header give strike, dip, rake (in degrees), the depth (in km) and the seismic moment (in units of 10^{18} Nm. The focal spheres are shown with the P and SH nodal planes in lower hemisphere projections. The solid and open circles mark the P and T axes, respectively. Surrounding the focal sphere, the observed P and SH waveforms (solid lines) are compared with synthetic waveforms (dashed lines) computed for the minimum misfit solution. These are ordered clockwise by azimuth. A letter corresponding to its position within the focal sphere accompanies the station code by each waveform. Solid bars at either end of the waveform mark the inversion window. The source time function is shown below the P-wave focal sphere, with the waveform time scale below this. Waveform amplitude scales are to the left of the focal sphere. This solution was obtained using a 10 km thick layer (Vp=6.00 km/s, Vs=3.47 km/s, ρ=2.69 kg/m^3) over a half-space (Vp=6.50 km/s, Vs=3.76 km/s, ρ=2.85 kg/m^3).

This solution was calculated using a velocity model consisting of a 10 km thick layer with Vp =6.00 km/s, Vs=3.47 km/s, and ρ=2.64 kg/m^3 over a half space with Vp=6.50 km/s, Vs=3.76 km/s, and ρ=2.85 kg/m^3. The observed waveforms are well matched by the synthetic waveforms for the first 60 seconds.

Figure 3 shows tests made of the source parameters. The figure compares selected P- and SH- waveforms of the minimum misfit solution (top line) with an inversion computed using the published CMT fault plane solution (s d r) and the Engdahl et al (1998) depth. The solution showed is a minimum in dip, depth, source time function and moment space, but is a much poorer fit than the minimum misfit solution shown in the first line. The third and fourth lines of Figure 2 show the effect of fixing the depth of the minimum misfit solution at 19 and 11 km. These fits are significantly worse than the match of the minimum misfit solution, leading to a depth uncertainty of ± 3 km.

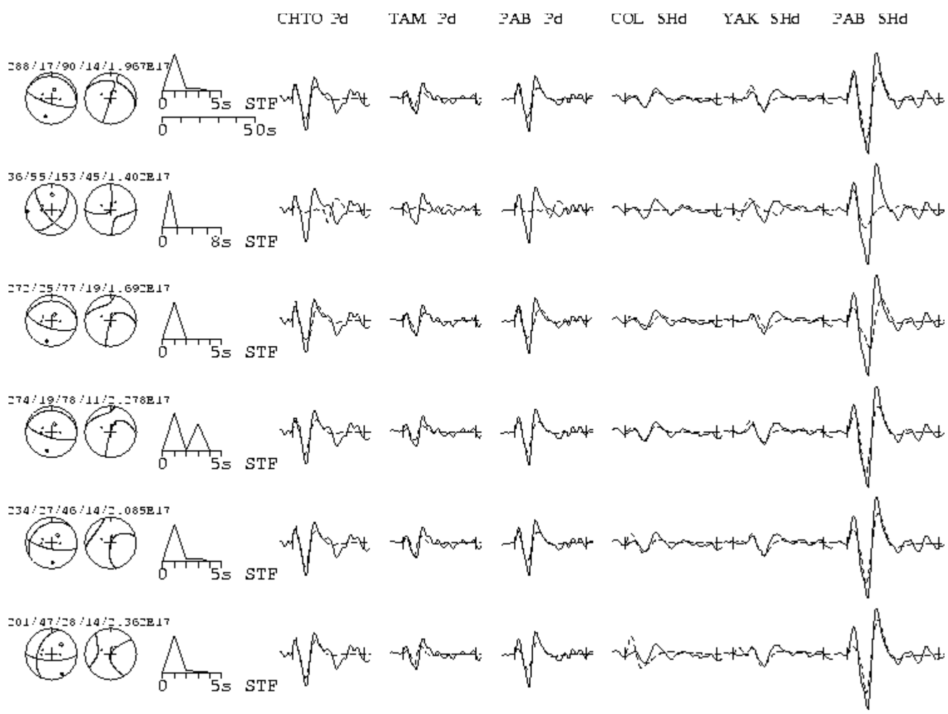

Figure 3. Waveform tests for the Zagros Mountains earthquake of July 31, 1994. (a) minimum misfit solution, (b) results for the inversion of the test of the Engdahl et al (1998) depth, (c) test of 19 km focal depth, (d) test of 11 km focal depth, and (e) and (f) test of the dip.

Cepstral Analysis

Another method used to determine depths that does not rely on waveform modeling is cepstral analysis. This method is based on an estimation of the spectrum of the log spectrum of windows of seismic data (called the *cepstrum*), and peaks in the cepstrum can be directly related to the event depth. As long as a seismic signal has sufficient bandwidth, cepstral analysis can be used to detect the delay times between P and depth phases such as pP and sP. We are using the cepstral F-statistic method (Reiter and Shumway, 1999) to estimate the depths of the same teleseismic events in Iran for which we have depth estimates from waveform modeling. The cepstral F-statistic method for depth estimation attaches statistical significance to peaks in the cepstrum through a signal-to-noise ratio computed from the beam cepstrum and the sum-stacked cepstrum. This is an advantage over traditional cepstral analysis because it allows us to assign validity to peaks in the calculated cepstrum. We estimate individual cepstra from windows of data that contain the P arrival and its coda, and the F-statistic is formed by dividing the beam (mean) cepstrum by the error between the beam and the sum-stacked cepstrum. This analysis can be performed on both array and single three-component station data. To be valid, peaks at possible depth phase delay times must appear in both the beam cepstrum and the F-statistic estimate and must be stable over varied processing parameters such as window length, start time and overlap. In addition, we window the signal portion of the log spectrum prior to calculating the cepstrum and performing peak detection. This is done to decrease the strong influence of out-of-band noise on the cepstrum and F-statistic. For more details about the method, please see Reiter and Shumway (1999).

We processed the data from the July 31, 1994 earthquake in the Zagros Mountains using a subset of the stations from the waveform analysis. This was based on distance from the earthquake and signal-to-noise ratios. Table 1. provides a list of the stations used, along with their epicentral distance, the number of windows input to the cepstral analysis algorithm and cut-off frequency in the detrended log spectrum. The results indicate a depth of 18 km (± 4km). We derived this result by assuming that the earlier peaks at stations ABKT, LVZ and KEV are due to the pP-P delay time and the later peaks at stations ABKT, WUS and GRFO are due to the sP-P time. Further analysis is necessary to confirm these results, but initial indications are that they agree fairly well with the waveform modeling results.

Table 1.

STATION	Δ	# Windows	Cut-off Freq (Hz)
ABKT	9.62	4	1.2
WUS	25.9	4	1.8
GRFO	32.4	4	2.1
LVZ	36.2	4	.95
KEV	39.1	4	2.0

CONCLUSIONS

In this study we are attempting to calibrate regional seismic stations in the Middle East using well-located moderate-size earthquakes. We are building a database of well-located events whose source parameters have been determined by teleseismic waveform modeling. Depth estimates of moderate-size earthquakes in Iran can be determined to ±3 km from this modeling analysis. The cepstral F-statistic method is being applied to provide an independent focal depth estimate. For the moderate-size earthquakes we have analyzed to date, the cepstral F-statistic method for hypocenter determination agrees well with the hypocentral depths found from the teleseismic waveform modeling.

Once we have developed a database of well-located events in the region, we will use the results from the moderate-size earthquakes to calibrate the regional seismographs. This work will result in a database of well-located, moderate-size events in Iran, a catalogue of small magnitude Iranian events whose focal depths are accurately known, and a calibrated procedure for depth determination in the region. We will also extend the cepstral method to smaller magnitude events in Iran and determine the minimum magnitude for reliable source depth.

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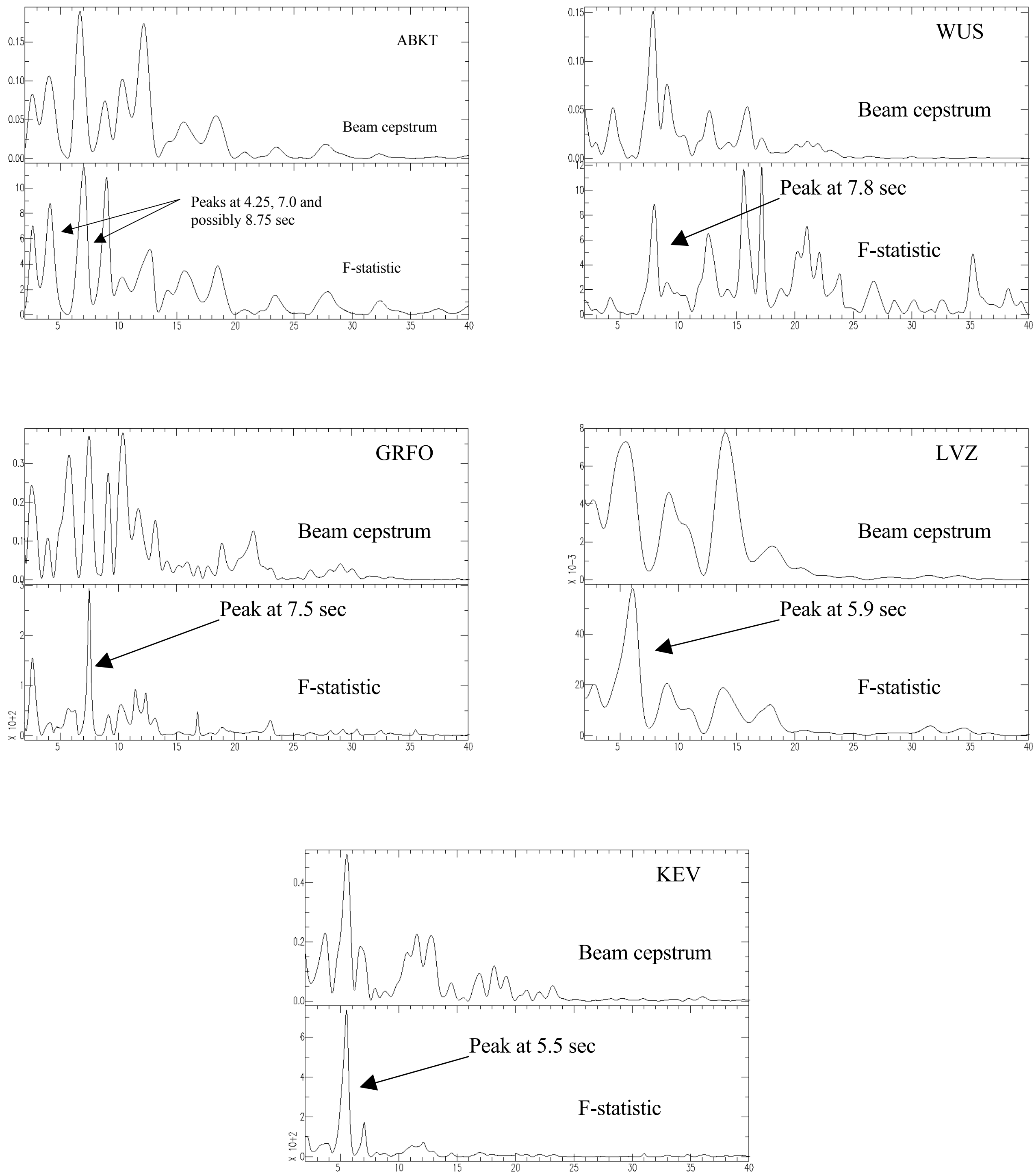

Figure 4. Results from cepstral analysis of the July 31, 1994 earthquake in the Zagros Mountains of Iran. We processed a subset of the stations used in the waveform analysis that had fairly high signal-to-noise ratios. Peaks in the beam cepstra and F-statistics indicate a depth of 18 km (± 4 km). This result was derived by assuming that the earlier peaks at stations ABKT, LVZ and KEV are due to the pP-P delay time, and the later peaks at stations ABKT, WUS and GRFO are due to the sP-P delay time.