SOURCE OF THE EARTHQUAKE DOUBLET OF 11TH AUGUST 2012, NORTHWESTERN IRAN, FROM OBSERVATION OF GLOBAL SEISMIC ARRAYS AND LOCAL NETWORKS

Alireza ALINAGHI
Assistant Professor, IIEES, Tehran, Iran
alireza.alinaghi@gmail.com

Keywords: Seismic Array, Hypocentral Depth, Seismic Source, Earthquake Mechanism

ABSTRACT

On August 11, 2012 two catastrophic earthquakes with moment magnitudes of 6.4 and 6.2, respectively, only 11 minutes and circa 5 kilometers apart, struck northwestern Iran which caused hundreds of casualties and left thousands of people homeless.

Based on the analysis of data from global seismic arrays and also those of the local and regional seismic networks, the hypocentral depth and mechanism of the first event and also the mechanism of the second earthquake have been determined. While the first event with complex rupture history, unusual for an earthquake of such magnitude, released the bulk of its energy through a mainly strike-slip dislocation in a second subevent, approximately 5 seconds following the P onset and at a depth of around 5 kilometers, the second earthquake, shows a mainly reverse faulting and seemingly simple rupture history and deeper hypocentral depth.

Both events have occurred where no active fault had been mapped in their vicinity and once again questions have been raised as to how much weight in seismic hazard assessments should be placed on known active faults.

INTRODUCTION

The studied doublet has occurred in a region which is seismically active and seismotechnotically located in a complex interaction of Zagross subduction remnants, Talesh and Alborz mountains and east and north Anatolian faults regime. Proximity of such varying tectonic provinces has given the earthquakes in this region a varied and complex nature (Fig 1).

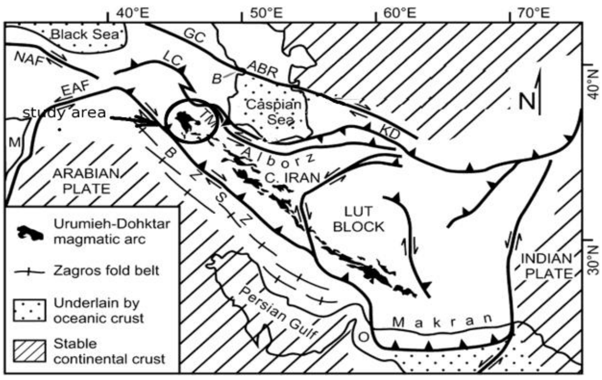
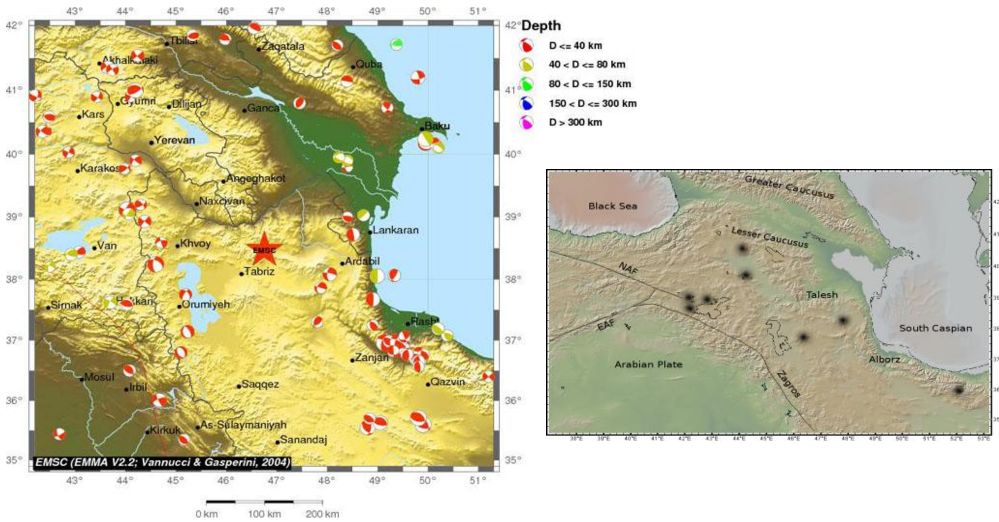


Figure 1. The location of the epicentral region (circle) in a simplified map of major tectonic elements such as East and North analotian faults, Alborz mountains and Zagross main thrust. (after Axen et al, 2001)

Although the main driving force to be considered is the northward oblique convergence of Arabian plate against Iran, which is reflected in reverse and strike-slip mechanisms of earthquakes, rotation of the south Caspian block against northern Iran has been considered an additional factor resulting in normal component of movement in earthquakes occurring in the region (fig. 2).



a b

Figure 2. Location of the epicentral region marked with red star (a) with focal solutions of major earthquakes in the region in which events with components of normal faulting are located both east and west of the epicentral region. Further evidence of tensional regime is also reflected in existence of a number of volcanoes located in the region and marked with black dots (b).

DATA

To detect and enhance seismic phases for determination of hypocentral depth and detection of subevents using array techniques, teleseismic seismograms of global stations at epicentral distances of 30-95 degrees have been used. Care has been taken to pick records of stations with close proximity to form a local array and hence increasing the waveform coherence. Mainly broadband data have been used. IIEES broadband stations and boradband records of neighboring neighboring countries have also been used for inversion to determine focal mechanism and constrain the depth of the doublet.

METHODOLOGY

Array techniques beamforming, F-K analysis and slant stacking have been used to isolate, identify and enhance depth phases in order to determine the hypocentral depth at teleseismic distances.. However, successful application of such methods across arrays depends on prior knowledge of source mechanism and duration of source time function in order to distinguish depth phases from subsequent subevents. Since good azimuthal coverage of recording global arrays for unambiguous phase identification is seldom achieved, broadband stations in various azimuthal windows which have close proximity are used to simulate an array of seismographs and to provide coherent signals for analysis.. Modeling of beams for for minimizing false interpretation of depth phases has been carried out using 1D velocity models and F-K method.. To avoid misidentification of multiple rupturing as depth phases SH component of S wave have also been modeled and observed. The S wave, with respect to its different propagation pattern than P gives us more flexibility when azimuthal coverage of the studied earthquake is limited. The result of such observation and consequent modeling have also been presented accordingly.

Full waveform inversion of long period content of broadband data from stations surrounding the epicentral region has been performed to solve for moment tensor components. The use of seismic waves at long periods improves the estimation of earthquake source parameters because they are relatively insensitive to the effects of lateral velocity and density heterogeneities (e.g., Ritsema and Lay, 1995). We have used the matrix inversion method in time domain to invert for the point source moment tensor using Green's functions computed from 1D velocity models (Ichinose et al., 2003). For periods of our observation (20-50 sec), we are able to use the point source assumption which does not model the complexities that arise from source finiteness and path propagation effects. In order to account for errors in epicenter location we have run the inversion for a grid of points 0.5 degree around the teleseismic epicenter and took node of the highest variance reduction as the location of earthquake for calculation of Green functions. Further we have calculated a suite of 1D velocity models as variations from a simple two-layer model to more realistic models derived from other studies. Green functions were also computed for these suites of models for 2 km depth increments prior to inversion. The Green's functions are computed using a fast reflectivity and frequency-wavenumber (*f*-*K*) summation technique (Mueller 1985; Zeng and Anderson, 1995). The sources and receivers are distributed across different tectonic regions, and therefore the choice of the velocity model used in the moment tensor inversion depends more on site and path velocity structure than on source structure. We have solved for the full moment tensor (6 degrees of freedom moment tensor) and also for the deviatoric moment tensor (5 degrees of freedom moment tensor). With the 5 degrees of freedom moment tensor, we assume there is no volume change (no isotropic component) and replace the moment tensor element **Mzz** with -(**Mxx + Myy**).

RESULTS

We present our findings concerning the source time function, source depth and also the mechanism of the doublet.

1. The First Event (Origin Time: 2012-08-11 12:23:18 UTC, Mw=6.4)
2. **2.** The Second Event (Origin Time: 2012-08-11 12:34:35 UTC, Mw=6.2)

At teleseismic distances a major high amplitude phase 4-5 seconds after the P onset, seems like a depth phase. However, closer examination proves that it is a major subevent which has released most of the earthquake energy. To verify our hypothesis we analyze the event's P and S phases at all azimuthal coverages that data permit. And, to find out about the source time function and considering the focal mechanism of the event, we analyze the event at those azimuths where depth phases have negligible amplitudes. For the azimuthal range 25-65 we expect strong P onset with insignificant amplitudes of depth phases. Here we will see the shape of the source time function without the interference of depth phases (Fig. 3).

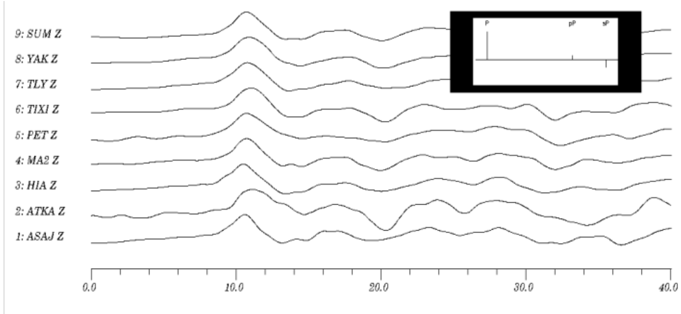


Figure 3. Displacement seismograms for the azimuthal window of 20-55 in which strong P onset is almost free from depth phases (the inset shows the expected amplitude-polarities)

On the other hand, in order to find the trace of source time function on SH components, we calculated the synthetics and found out that for the azimuthal range of 80-110 we can have the source time function of the earthquake without interference from depth phases (Fig.4).

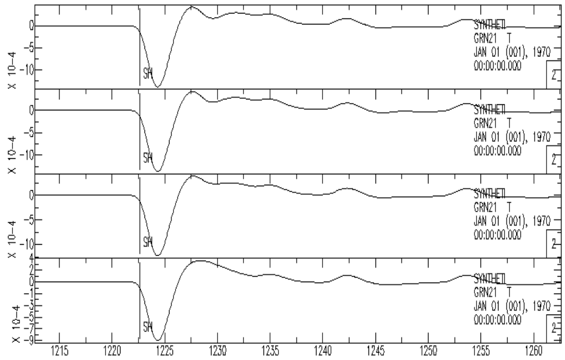


Figure 4. Velocity SH synthetics for a depth of 10 km at azimuthal range of 80-110, showing clear trace of STF

The corresponding stack of SH components for the same azimuthal range shows the source time function of the earthquake (Fig. 5).

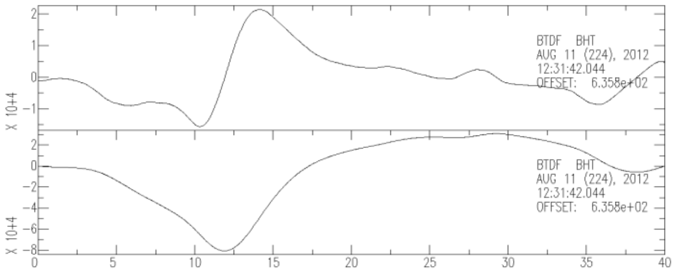


Fig. 5 Velocity stack (top) and displacement stack (bottom) of SH components of the event for the azimuthal range of 80-110 degrees.

Scrutiny of both P and SH components of source time functions show that the major subevent releasing most of the energy of the event is preceded by a smaller event, almost one degree of magnitude smaller, at about 5 seconds earlier. We do not have strong evidence as to the mechanism of the smaller subevent but it seems that its mechanism has deviation from the main subevent. The depth of the major subevent, can be estimated by identification of its depth phases in various azimuthal ranges where depth phases have significant amplitudes. One azimuthal span of interest which is covered by data, is 0-10, where both direct P wave and the sP phase, are prominent (Fig. 6).

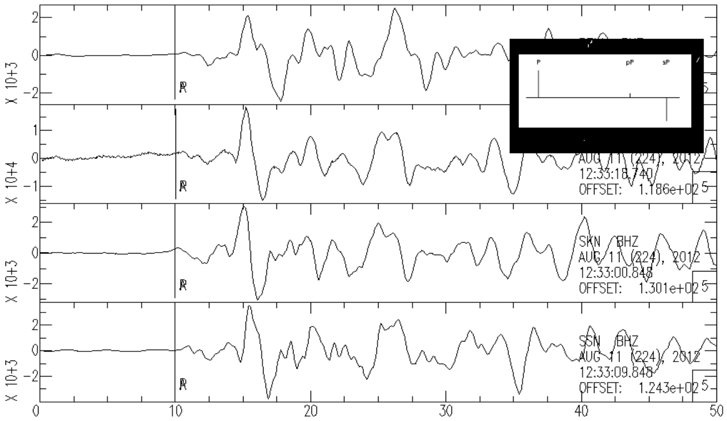


Figure 6. The major subevent following the P onset for selected broadband teleseismic recordings in azimuthal range of 0-10 degrees. The inset represents the polarity and amplitude of the P onset and depth phases.

Since we are interested in polarity observed phases, only broadband data are shown where polarity are preserved. Data of ILAR array, located in this bearing, on the other hand, due to its short period nature, can only help with identification of depth phases and does not help much with polarity study of depth phases which are in the P coda. In the azimuthal range of 305-330 with GRF array located at the bearing of 305 with respect to the earthquakes, the sP phase is clearly seen while direct P and pP phases have negligible amplitudes. Across this array an interesting feature of seismograms is a major phase that follows the sP phase 3-4 seconds later. This is another complexity of this event which in our opinion is a source signature and can be attributed to another pulse in rupture history. Observing data of Yellowknife and ILAR arrays for the main event of the doublet and comparing them with those of second event can explain why fit of the data specially for the coda of P wave and surface waves have become difficult. USGS body-wave moment tensor solution puts the depth at 3 km, in accordance with our depth estimate of major subevent. While the centroid moment tensor solution puts it at 10 km. And according to Harvard CMT solution, it is estimated to be 12.6 km. The interesting feature of all these solutions is variation of dip and dip direction of both planes, which shows these are not well-constrained.

We have used broadband data from Iran National Seismic Network, operated by IIEES, Iran and data provided by IRIS from broadband stations in neighboring countries (Turkey and Armenia) to model the earthquake source. In order to conduct the inversion, first a crude velocity model consisting of a 55 km thick crust of 55 overlying half-space was adopted. Then a variety of frequency bands were tested and both variance reduction and scalar moment magnitude were monitored. It was ascertained that for frequency band of 0.02-0.05 Hz the best match is obtained. Since we do not have reliable high resolution local velocity model and with respect to complexity of the event, also by trial and error and observation of fit of data with the synthetics and variance reduction, those stations were picked from the whole data set that delivered the best results. The next step was to run the inversion for a grid of coordinates, 0.1 degree apart and encompassing the epicenter coordinate as reported by USGS. The inversion was made for deviatoric seismic tensor, which excludes isotropic element. Map of variance reductions for solutions with more than 70% of double-couple component was finally plotted (Fig. 7).

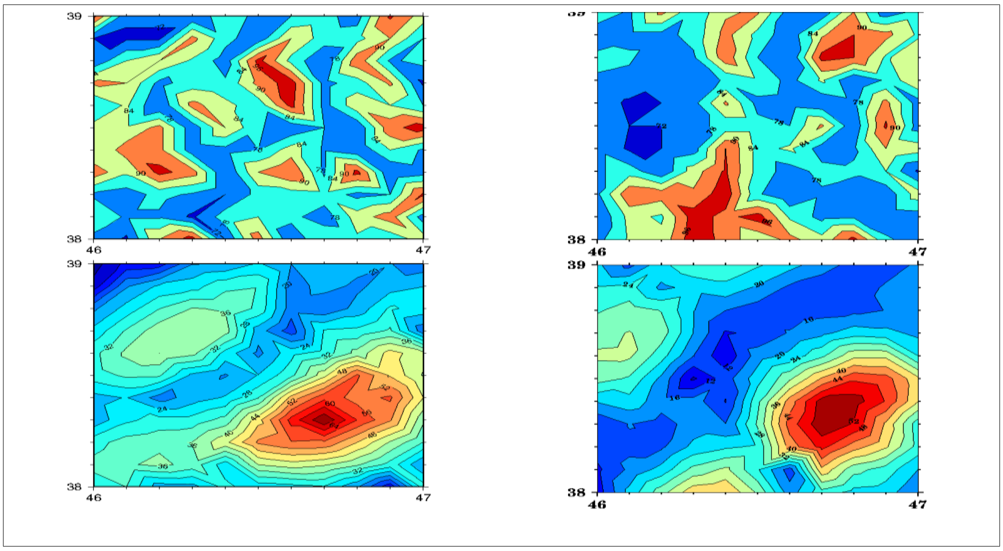


Figure 7. Maps of variance reduction (bottom) and DC component of seismic moment (top) across the epicentral region for the main event (left) and the second shock (right).

The coordinates for which the variance of fit of data and synthetics marked the highest reduction-lat:38.4, lon:46.8, was chosen and Green Functions were recalculated for a suite of velocity models, starting from a 6 layer model (S. Donner 2012, personal communication) which is based on surface wave studies in Central-Alborz, northern Iran to arrive at the most realistic model. It was proven that the choice of velocity model for low frequency band of our study improved the results only slightly. The final inversion was run for increments of depth as well as shifts in origin time. The result of the inversion (Fig. 9) shows a large strike-slip slip component of rupture with a more or less east-west striking plane suspected of being the causative fault, based on the distribution of aftershocks and measurements of rupture dislocation on the ground, made following the occurrence of the earthquake doublet (Tatar, personal communication). It must be noted that variance reduction when both Turkish and Iranian stations were included in the solution (as presented here) has not exceeded 65% which is rather low.

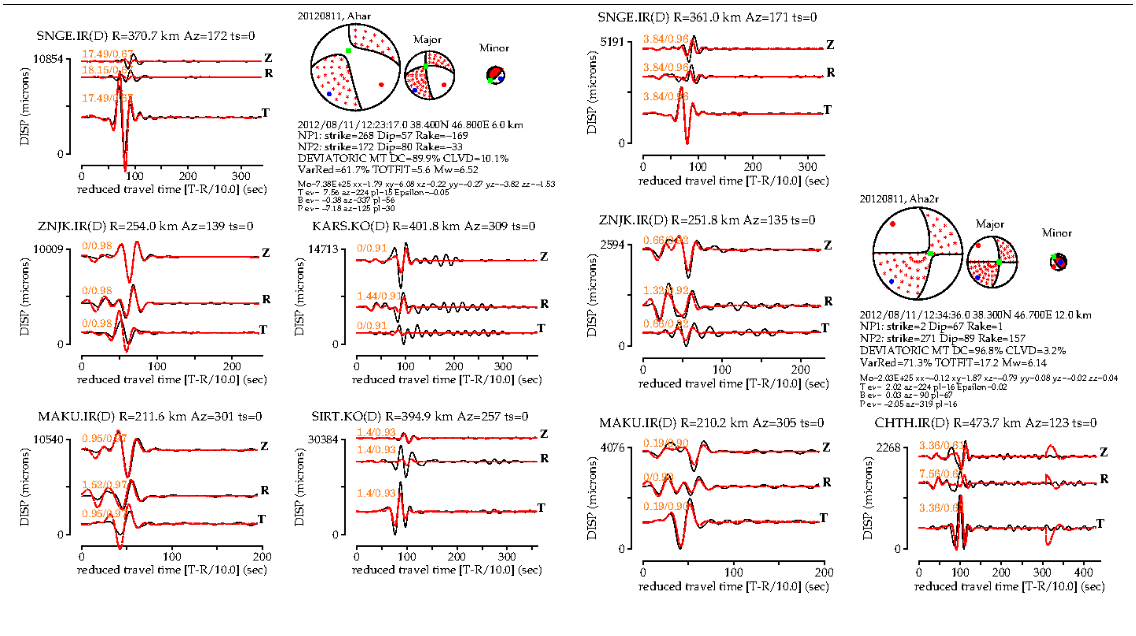


Figure 8. Solutions for the main event (left) and the second earthquake (right) of the earthquake doublet.

This could lie in the complex nature of the main shock both in terms of multiple rupturing which compromises point source assumption, and also extended P coda, best known at teleseismic distances (e.g. GRF and YK arrays). It must be noted that inverting for the full moment tensor, by including the isometric element of the motion, did not significantly improve the fit nor variance reduction.

The second event which occurred about 11 minutes after the first shock was also analyzed with the same approach as the main event. In contrast to the main event, the second event measured 6.2 on moment magnitude, which occurred about 11 minutes following the main shock was examined in various azimuthal spans (e.g. in US array, Fig. 9).

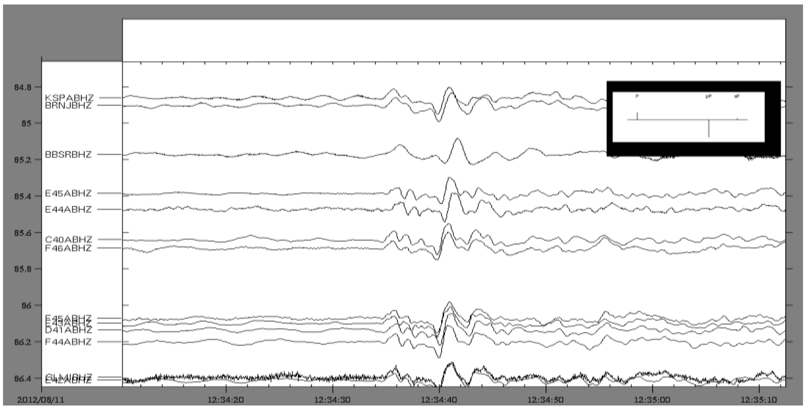


Figure 9. Vertical component seismograms of the 2nd event of the double as recorded in one of the subarrays of USARRAY showing positive P onset followed by depth phases about 4-5 seconds afterwards with expected polarities (the inset).

Through modeling it showed a simple rupture with a depth of around 14 km (Fig. 10).

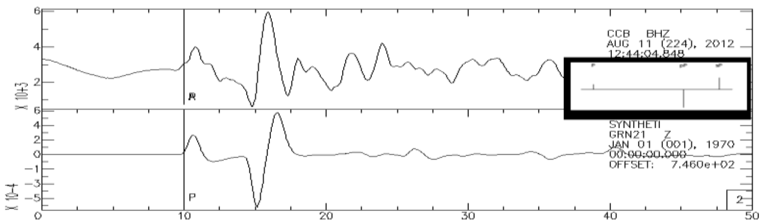


Figure 10. Teleseismic modeling of the 2nd event of the doublet as recorded in a broadband station (CCB) with a bearing of 5 degrees, showing the P onset as well as the depth phases for a hypoenter depth of 14 km. The inset is the stick diagram showing expected polarities.

Moment tensor solution of this event was carried out with the same approach as taken for the main shock. Accordingly Green functions were calculated for a grid of points with spacing of 0.1 degree, which showed the highest amount of variance reduction at the location: lat:38.3 lon:46.7, which is located southwest of the main event. The results of the inversion show higher component of reverse faulting compared to the main shock (Fig. 7 & Fig. 8).

CONCLUSIONS

Present study of the catastrophic earthquake doublet that hit northwestern Iran, has revealed complexities inherent in the rupture process of the main shock. A major rupture phase which has released most of the seismic moment of the earthquake is preceded with a smaller subevent, 4-5 seconds and is followed by a complex and rather lengthy P coda, being suspect of masking some other rupture events. Whether the major phase being of rather shallow depth is the stopping phase of a rupture process or just marking a major asperity needs further attention and study. Not much can be said about the mechanism of the starting subevent. However polarity of P onset in recording regional stations as well as some waveforms features of it appearing at teleseismic distances in densely located broadband stations or seismic arrays bear witness to its similar mechanism as that of the main rupture phase. However, the depth of this starting subevent is further a subject of speculation; whether it is of the similar depth with the main phase or so deep that its depth phases are masked by the following major phase need be investigated further. Analysis of the records of the main shock at teleseismic distances in global seismic arrays as well as broadband seismograms of global stations with proximities to allow for waveform coherence, has revealed depth phases of the major rupture phase that agree with a shallow depth of around 3-5 km . However, in some azimuthal spans, some entailing phases and complexities are observed in the P coda following the main rupture phase that have yet to be explained. These intricacies have probably contributed to variations in dip angle and direction observed in various moment tensor solutions reviewed in this study.

Moment tensor analysis of the main shock carried out in a grid of points surrounding the globally determined epicenter of the earthquake for a suite of velocity models and frequency bandwidths have enabled us to pinpoint the location of the earthquake centroid, i.e., where most of the seismic moment has been released. This spot is in good agreement with Harvard centroid location and has been taken as the location of the event for final inversion using station which delivered the most stable and highest amount of variance reduction. The mechanism thus obtained shows a high percentage of double-couple and a large component of strike-slip faulting. Depth of the earthquake for which the variance reduction has been the most, has been determined 6 km which does not disagree with results obtained by identification of depth phases in global arrays, but considering the large period of waveforms analyzed is subject of uncertainties.The second event of the doublet is on the other hand composed of a single rupture and had initiated according to our analysis of teleseismic records of array data at the depth of 14 km. This result was also substantiated by modeling. Moment tensor solution of the second event, carried out the same way as the main shock, revealed the centroid of the event southwest of the main shock and has a larger component of reverse faulting than that of the main event. The depth of this event as reduction of variance indicates is at the depth of 12 km. The second event in contrast to the main shock does not show complexities of waveform as the main quake nor does it have the prolonged complex P coda following the depth phases.

REFERENCES

Axen GJ, Lam PS, Grove M, Stockli DF and Hassanzadeh J (2001) Exhumation of the west-central AlborzMountains, Iran, Caspian subsidence, and collision-related tectonics, v. 29, p.559-562

Ichinose Gene A, John G, Anderson, Ken D. Smith and Yuehua Zeng (2003). Source Parameters of Eastern California and Western Nevada Earthquakes from Regional Moment Tensor Inversion, Bull. Seismol. Soc. of America, 93, 61 -84

Mueller G (1985). The reflectivity method: a tutorial, J. Geophys. 58, 153–174

Ritsema J and Lay T (1995). Long period regional wave moment tensor inversion for earthquakes in the western United States, J. Geophys. Res. 100, 9853–9864

Zeng Y and Anderson JG (1995). A method for direct computation of the differential seismogram with respect to the velocity change in a layered elastic solid, Bull. Seism. Soc. Am. 85, 300–307