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Focal mechanisms of M_w 6.5, March 31. 2006 Iran- Silakhor earthquake using data from the Iranian Seismic Network

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Abstract

The source parameters and focal depth of the destructive M_w 6.5, 31 March. 2006 Iran-Silakhor earthquake, the two largest foreshocks and a major aftershock are determined using broadband data from a seismic network in Iran based on a time-domain linear moment tensor inversion. The earthquakes occurred in the Zagros Suture zone in western Iran. Waveform inversion of the selected events estimated focal depths in the range of 15–20km which limits the brittle–ductile transition zone beneath parts of the studied area. The dominant double-couple part of the moment tensor solutions for most of the events indicates that the analysis is working reasonably well and that the amplitudes at the individual stations are not too disturbed by local structure or noise. Re-evaluation of the analyzed events shows predominantly right-lateral strike-slip faulting consistent with the relative motions of the significant faulting in the region.

Key words: Iranian Seismic Network, Moment tensor inversion, Zagros Suture,

سازوکارهای کانونی زمین‌لرزه ۱۱ فروردین ۱۳۸۵ سیلاخور، پیش‌لرزه‌ها و پس‌لرزه‌های آن براساس داده شکل موج ایستگاه‌های لرزه‌نگاری ایران

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چکیده

زمین‌لرزه‌ای با بزرگی M_L=6.1 (IIEES) و M_W=6.5 (تحقیق حاضر) در ساعت ۰۴:۴۷:۰۲ (به وقت محلی) بامداد ۱۳۸۵/۰۱/۱۱ در مجاورت روستای درب‌آستانه دشت سیلاخور به مختصات جغرافیایی ۳۳٫۶۵ درجه عرض شمالی و ۴۸٫۹۱ درجه طول شرقی از توابع شهرستان بروجرد رخ داده است که در همه استان‌های هم‌جوار احساس شد. این زمین‌لرزه دارای دو پیش‌لرزه بوده است که این امر باعث حساسیت مردم منطقه و خروج شبانه اهالی از اقامتگاه‌ها شد؛ به‌گونه‌ای که تلفات انسانی ناشی از زمین‌لرزه اصلی به کمتر از ۷۵ نفر تقلیل یافت (قابل‌مقایسه با زمین‌لرزه پنجم دی‌ماه ۱۳۸۲ بم که با همین بزرگی بیش از ۲۶۰۰۰ تلفات انسانی به‌بار آورد). این زمین‌لرزه با توجه به بزرگی و موقعیت آن در اکثر ایستگاه‌های لرزه‌نگاری داخل کشور ثبت شد. ثبت رقمی رویدادهای لرزه‌ای در ایستگاه‌های محلی اهمیت زیادی برای تحلیل پارامترهای منبع زمین‌لرزه دارد. در این مقاله محاسبه سازوکارهای کانونی براساس

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مدل‌سازی شکل موج دو پیش‌لرزه، زمین‌لرزه اصلی و چند پس‌لرزه ثبت شده در ایستگاه‌های لرزه‌نگاری باند پهن پژوهشگاه بین‌المللی زلزله‌شناسی و مهندسی زلزله صورت‌گرفته است.

در این پژوهش از روش مدل‌سازی شکل موج (آکی و ریچارد، ۱۹۸۰) برای محاسبه سازوکارکانونی و سایر پارامترهای منبع رویدادهای لرزه‌ای استفاده شده است. علاوه‌برآن، لایه‌بندی زمین به صورت افقی برای فاصله‌های منبع – گیرنده ۱۳۵–۱۵۰۰ کیلومتر مطابق روش توسعه یافته سای‌کیا (۱۹۹۴) برای روش بسامد – عدد موج مورد استفاده قرار گرفته است. برای بهینه‌سازی عمق رویدادهای لرزه‌ای روش‌های متعددی مورد بررسی قرار گرفته است (برای نمونه روش درگر و هلمبرگر، ۱۹۹۰) در این راستا سعی شده است تا همهٔ احتمالات برای عمق های ۵– ۵۰ کیلومتر در فرایند بهینه‌سازی عمق رویدادها در نظر گرفته شود.

نتایج این پژوهش روشن می‌سازد که سازوکار غالب برای رویدادهای بررسی‌شده، از نوع راست‌گرد امتدادلغز است که این نتیجه با خصوصیات گسل اصلی عهد حاضر (در گستره دورود – بروجرد) هم‌خوانی دارد. برازش مناسب شکل موجها روی هر سه مؤلفه لرزه‌نگاشت‌های ثبت شده در ایستگاه‌های محلی، دقت نتایج به‌دست آمده را مورد تأیید قرار می‌دهد. تعیین عمق رویدادهای لرزه‌ای با مدل‌سازی شکل موج از نتایج دیگر این پژوهش است. محاسبات ما عمق رویدادهای لرزه‌ای این ناحیه را بین ۱۵ الی ۲۰ کیلومتر نشان می‌دهد که در پوسته بلورین منطقه محدود شده است.

واژه‌های کلیدی: زاگرس، گسل اصلی عهد حاضر، زمین‌لرزه سیلاخور، سازوکارکانونی، مدل‌سازی شکل موج

1 INTEODUCTION

On March 31, 2006 at 01:17:02 (UTC time) , a strong earthquake occurred in western Iran, with M_L=6.1 (IIEES) and M_w 6.5 (present study). This was preceded by two large foreshocks and followed by a large number of aftershocks. Although the aftershocks were relatively small (with local magnitude less than 5.3), many of them were recorded at local and regional stations. This earthquake (Silakhor) caused extensive damage to many buildings over a large area in Lorestan province. Historical seismicity shows that the region has been subjected to at least one large destructive earthquake (Berberian, 1995). The section known as the Main Recent Fault near the epicenter of the March 31, 2006 earthquake caused an earthquake with magnitude 7.4 in 1909 (Ambraseys and Melville, 2005). Several strong earthquakes subsequently occurred near this event. The most recent was a magnitude 6.4 event that struck on June 22, 2002 located in the north-west of the region. The source area of the March 31, 2006, earthquake lies in a convergent tectonic setting, the Zagros region, where the Arabia plate collides with the Eurasia plate. The Arabia-Eurasia collision deforms an area of ~3,000,000 km^2 of continental crust, making it one of the largest regions of convergent deformation on Earth (Allen et al., 2004). The seismic activity of the region represents a major socio-economic threat to the further development of the region and emphasises the need for detailed analysis of the characteristics of the earthquake sources.

The study and understanding of a wide range of earthquake related phenomena such as rupture characteristics, seismic hazards, crustal stress and regional tectonic evolution are related, to some degree, to the determination of earthquake source parameters. Higher frequency seismic waves at local distances contain useful information about the state of the seismic source that can be extracted (e.g. by inverse methods). The main purpose of the present paper is to analyze the seismic source parameters of the two largest foreshocks, the mainshock and the major aftershocks of the March 31, 2006, Silakhor earthquake using local and regional broadband data from Iran. In addition to focal mechanisms, the scalar seismic moments, moment magnitudes and optimal focal depths are also determined.

2 TECTONIC SETTING

Iran lies in the wide boundary that separates the Arabia and Eurasia plates. The Zagros Suture, in the western part of Iran, marks the present southern side of the broad collision zone of the Arabia-Eurasia plates. The 10 mm yr^{-1} convergence in the central Zagros region (Tatar et al., 2002) is likely to be a minimum value for the eastern Zagros area, given that the total Arabia-Eurasia convergence rate increases eastward. Therefore, using a convergence rate of 26 mm yr^{-1} (in the western part), a maximum of ~16 mm yr^{-1} remains to be accommodated between central Iran and stable Eurasia. This must result in a comparable amount of right-lateral shear on north-south strike-slip faults along the eastern margin of Iran. The March 31, 2006 event occurred close to the Zagros Main Recent Fault, a major strike-slip fault.

3 DATASET AND IRANIAN SEISMOLOGICAL NETWORK

Two main seismological networks currently operate in Iran. The national short period seismic network operated by the Institute of Geophysics, University of Tehran (IGTU, http://geophysics.ut.ac.ir/En/) consists of 54 seismic stations across the country (figure 1a, triangles). Most of the sensors are located in boreholes and are equipped with a 3-component seismometer with an eigenfrequency of 1.25 to 1.0Hz (negative feedback SS-1 Ranger Seismometers). The second network is the Iranian National Broadband Seismic Network (INSN) which consists of 14 three-component Guralp CMG-3T sensors operated by the International Institute of Earthquake Engineering and Seismology (IIEES, http://www.iiees.ac.ir/english/index_e.asp), (figure 1a, circles). Via VSAT, waveform data from the INSN broadband network are transferred in real time to the main building of IIEES in Tehran with a sampling rate of 50Hz. The Guralp CMG-3T sensors in the INSN have a flat velocity response in the period range from 0.02 to 100sec.

A number of foreshocks of magnitude between 4.0 and 5.2 were observed prior to the March 31, 2006 Silakhor earthquake, which was also followed by many aftershocks, with magnitudes 2.0-5.3. As shown in figure 1c the source area coincides with the NW trend of pre-existing faulting in the area and the associated earthquake sequence indicates north-westward slip propagation. We studied 4 earthquakes from the source area of the March 31, 2006 earthquake, the two largest foreshocks, the mainshock and a major aftershock. The earthquakes selected have high signal to noise ratios and are recorded by 10 broadband seismic stations in Iran. The source parameters of the earthquakes studied are listed in table 1.

4 METHODOLOGY OF WAVEFORM MODELLING

According to the representation theorem (Aki and Richards, 1980), the far-field displacement components, un(x,t), from a seismic source of a seismic moment $M_{ij}(\xi,\tau)$ which is localised precisely both in space and time, can be described in terms of Green's functions, $G_{ni,j}(x,t,\xi,\tau)$, as

$$u_n(x,t) = G_{ni,j}(x,t;\xi,\tau) * M_{ij}(\xi,\tau) \tag{1}$$

where * denotes convolution, x and t are the coordinates at the receiver; ξ and τ are the coordinates at the source; i, j, n are directions of the coordinate system. Assuming a synchronous source (i.e. all components of the time dependent moment tensor have the same time dependency), a linear weighted least squares scheme can be used to retrieve the moment tensor components in the time-domain. We calculate the far-field response of an arbitrary oriented shear dislocation point source in a plane layered media using the frequency-wavenumber method developed by Saikia (1994) at different local epicentral distances (135-1500km).

The accuracy of moment tensor inversion is dependent on the accuracy of the Green’s functions calculation. Knowledge of Earth structure, necessary to calculate Green’s functions, is always limited to some level of detail. We have examined different velocity models available for the Iranian plateau. The seismic stations used are situated in different tectonic environments implying that Earth structure could have significant effects on the response at the different stations. However, insufficient data exists to define a robust three-dimensional velocity model for the area, and we therefore decided to use a model which represents the main characteristics of the propagation path as listed in table 2. After correcting for the effect of the instrument responses and band pass filtering, the observed data were integrated to the corresponding displacement ground motion. Horizontal components were rotated, based on the back-azimuth, to form radial and tangential components. Good quality waveforms from vertical and rotated horizontal components were then selected from seismic stations at epicentral distances of 135-1500km. The inversion results are presented as the major double couple component and a CLVD part which stands for compensated linear vector dipoles. Data processing was performed using the SAC2000 (http://www.llnp.gov/sac/) (Seismic Analysis Code, Lawrence National Laboratory) package. Moment tensors were computed using the mtpackagev1.1 package developed by Douglas Dreger of the Berkeley Seismological Laboratory, and Green’s functions were computed using the FKRPROG software developed by Chandan Saikia of URS. (www.seismo.berkeley.edu/dreger/mtindex.html)

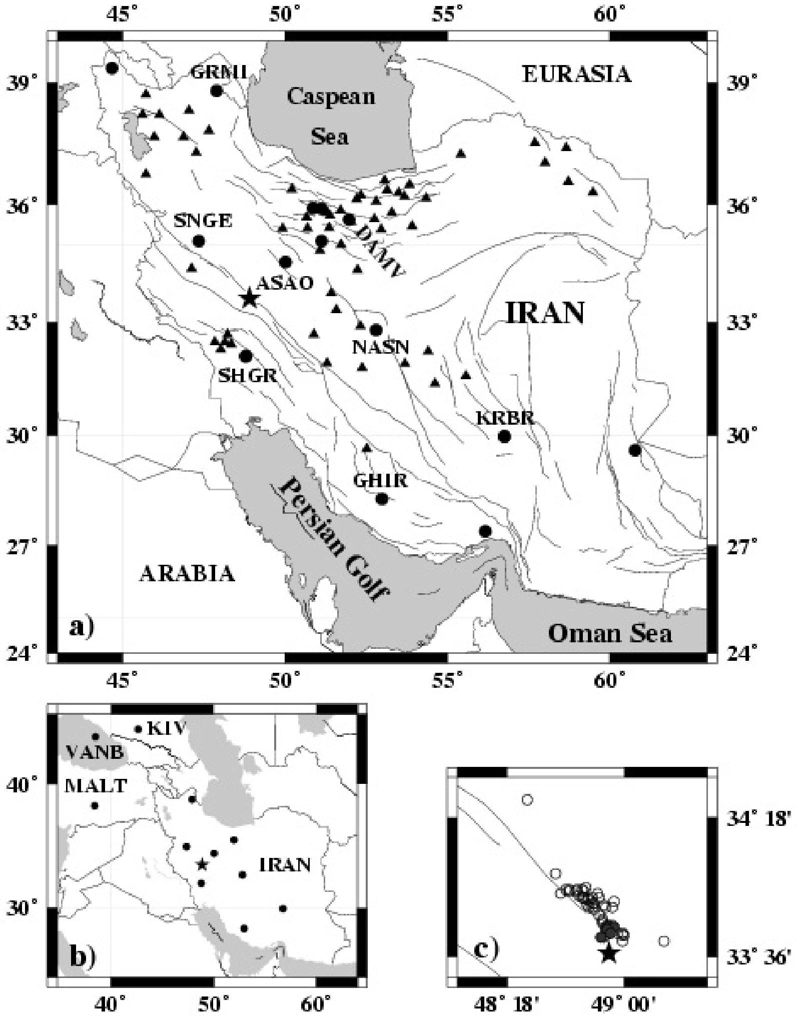

Figure 1. a) Distribution of short period (triangles) and broadband (circles) seismic stations in Iran, those used in the current study are named. The epicentre of the M_w 6.5 March 31, 2006 Silakhor earthquake is denoted by a star and the major faults are also depicted. b) Distribution of broadband seismic stations used in the inversion. c) Epicentres of the main shock (star), the foreshocks (filled-circles) and aftershocks (open-circles) of the March 31, 2006 Iran, earthquake.

Table 1. source parameters of earthquakes studied.

yymmdd_hhmm	sec	lato	lono	Depth (km)	mag	str1	dip1	rak1	str2	dip2	rak2	Mrr	Mtt	Mpp	Mrt	Mrp	Mtp	M_0 (dyne-cm)	source
060330_1617	0.60	33.75	48.90	14.0	$4.6M_L$														IIEES, IGTU
060330_1936	16.00	33.70	48.86	14.0	$5.1M_L$														IIEES, IGTU
060330_1936	21.00	33.65	48.78	19.5	$5.1M_w$	321	70	-167	226	77	-20	-1.32	-5.05	6.37	2.00	0.52	0.74	6.21e23	HRV_CMT
060331_0117	02.00	33.62	48.91	14.0	$6.1M_L$														IIEES, IGTU
060331_0117	09.90	33.74	48.73	17.0	$6.1M_w$	313	78	-174	222	84	-12	-0.33	-1.50	1.83	0.27	0.18	-0.15	1.71e25	HRV_CMT
060331_0117	02.22	33.63	48.80	27.0	$5.9M_w$	314	54	180	44	90	36	0.01	-0.83	0.82	0.42	0.43	-0.02	1.0e25	USGS_NEIC
060331_1154	02.00	33.89	48.79	14.0	$5.3M_L$														IIEES, IGTU
060331_1154	05.70	33.73	48.75	25.7	$5.1M_w$	319	67	-168	224	79	-24	-.39	-4.59	4.98	2.39	0.67	0.25	5.38e23	HRV_CMT

5 RESULTS OF WAVEFORM MODELLING

We conducted the moment tensor inversion in the time-domain in order to determine the focal mechanism of 4 earthquakes which occurred in the Zagros region based on broadband seismic stations in Iran. The use of stations at different distance ranges means very different signal amplitudes at the individual stations, which in the inversion can lead to an inappropriate dominance of data from the closest stations to the event. Therefore we have used a weighted linear least squares approach where weighting is proportional to distance travelled (Shomali and Slunga, 2000). Prior to inversion the observed data were zero-phase band pass filtered between 0.02-0.08Hz. The moment tensor inversion was performed under the deviatoric constraint (zero trace elements) and the results are presented as the major double couple and a CLVD source. Firstly, we present the waveform modelling of the mainshock,2006-03-31_01:17. Since this study is one of the first attempts to conduct the waveform inversion using data from the seismic network in Iran and also in order to investigate any bias due to the azimuthal coverage of the events used in our analysis, we inverted the mainshock under two different conditions. In the first attempt, only the broadband seismic stations in Iran have been used (figure 1b and table 3; case I) while in the second case the inversion was performed including 3 more stations from neighbouring countries at regional epicentral distances (figure 1b and table 3 case II). The waveform inversion results are shown in figure 2 for case II and the focal mechanisms are illustrated in figure 3. From the results it can be concluded that including 3 more stations at regional epicentral distances does not significantly change the results and the focal mechanism determined based on broadband stations in Iran alone provides a stable result comparable with other independent solutions (see figure 3). We then performed waveform modelling for other events (2006-03-30_16:17,2006-03-30_19:36 and 2006-03-31_11:54) using only broadband seismic stations in Iran. The inversion results are shown in figures 4, 5, and 6 and are listed in table 3 (case I). The inversion was carried out for all data together, i.e. not the tangential, radial and vertical components separately, and without weighting between the different components. The amplitude on the tangential component is generally significantly larger than on the others. This means that this component is likely to dominate in the inversion process. The waveform fit is better for the tangential components than for the other components, and the vertical components show a better fit than the radial components. Comparing focal mechanisms resulting from this study with other solutions independently derived for the events studied (see figure 3) we observe that our results are more coherent in the sense that the estimated focal mechanisms are more similar. For some very shallow earthquakes, the HRV CMT inversion does not well constrain the vertical-dip-slip components of the moment tensor (Mrt and Mrp),and thus these components are constrained to zero in that inversion, while our use of data at regional epicentral distances provides more reliable solutions. The relatively high percentage of CLVD in the sources can primarily be attributed to poor structural models of the complex tectonic characteristics of the area studied.

Table 2. Structural model used.

Thickness†) km	P velocity†) kms^{-1}	S velocity†) kms^{-1}	Density†) gcm^{-3}	Qp	Qs
6.0	5.4	3.12	2.8	600	300
8.0	5.9	3.14	3.3	600	300
4.0	6.3	3.64	3.3	600	300
28.0	6.5	3.76	3.3	600	300
26.0	8.05	4.65	3.3	600	300
	8.1	4.68	3.3	600	300

Table 3. Results of the inversion.

yymmdd_hhmm	str1	dip1	rak1	str2	dip2	rak2	Mxx	Mxy	Mxz	Myy
060330_1617	317	89	173	47	83	1	-3.89	-0.30	-0.29	3.60
060330_1936	48	85	7	317	83	174	-2.03	-0.17	0.04	2.20
060331_0117	51	89	20	320	70	179	-6.05	-1.35	1.45	7.02
060331_0117	50	89	18	320	72	179	-6.11	-1.25	1.31	6.95
060331_1154	313	86	173	43	83	5	-1.92	0.14	-0.07	1.93

Myz	Mzz	M_0 nm	M_w	DC %	clvd %	Variance	VarRed %	Var/Pdc	Depth km	source
-0.34	0.28	3.8	5.0	86	14	6.8e-08	64	7.9e-10	15	case I
-0.37	-0.17	21.5	5.5	80	20	2.5e-06	57	3.1e-08	15	case I
-2.20	-0.97	713.1	6.5	66	34	1.6e-03	70	2.3e-05	20	case I
-1.89	-0.84	700.6	6.5	71	29	1.2e-03	67	1.8e-05	20	case II
-0.29	-0.01	19.5	5.5	95	5	7.6e-07	76	8.0e-09	20	case I

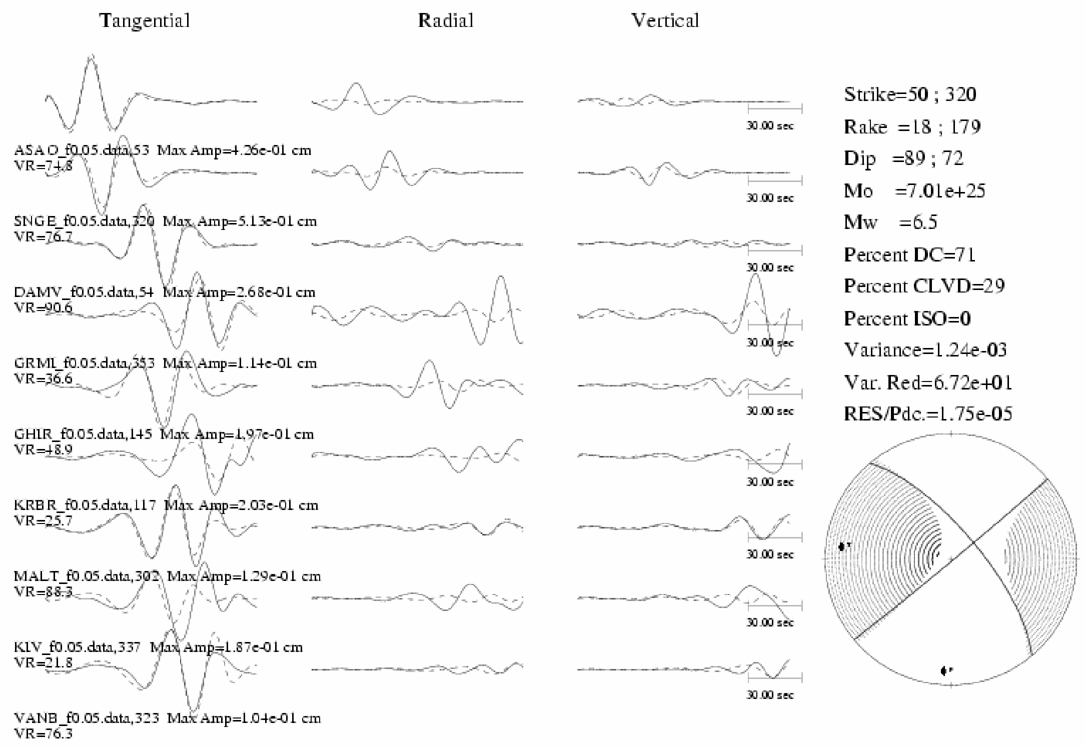

Figure 2. Moment tensor inversion results for the main shock, 2006-03-31_01:17. The solid-lines are the observed data and the dashed-lines are synthetics. The numbers beneath each waveform refer to the maximum amplitude and variance reduction

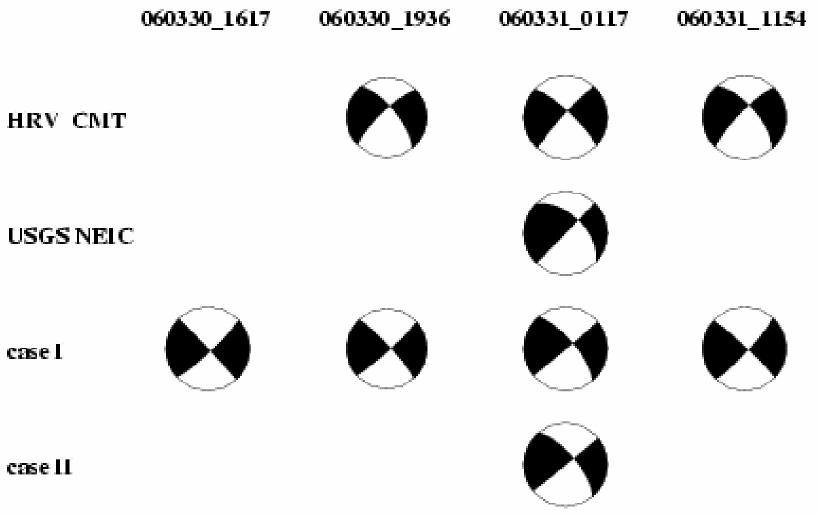

Figure 3. Focal mechanism obtained from the current study (third and fourth rows) and those from Harvard CMT and USGS NEIC solutions (first and second rows).

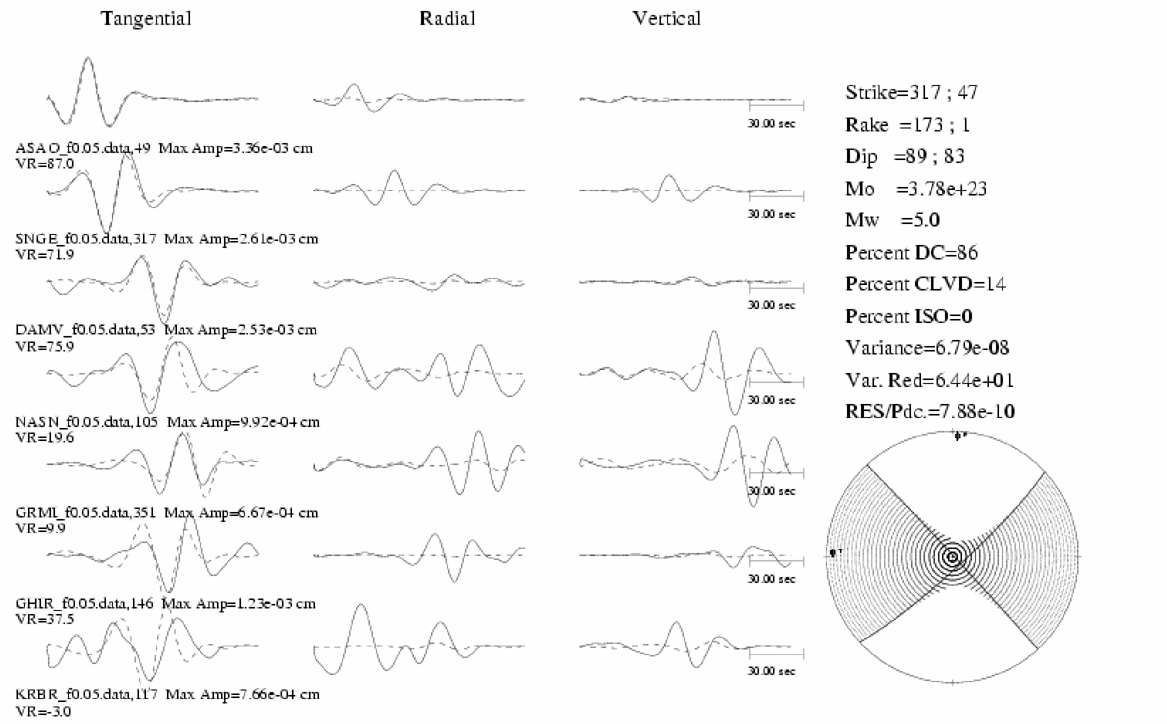

Figure 4. Moment tensor inversion results for the foreshock, 2006-03-30_16:17 (for other parameters see the caption of figure 2.).

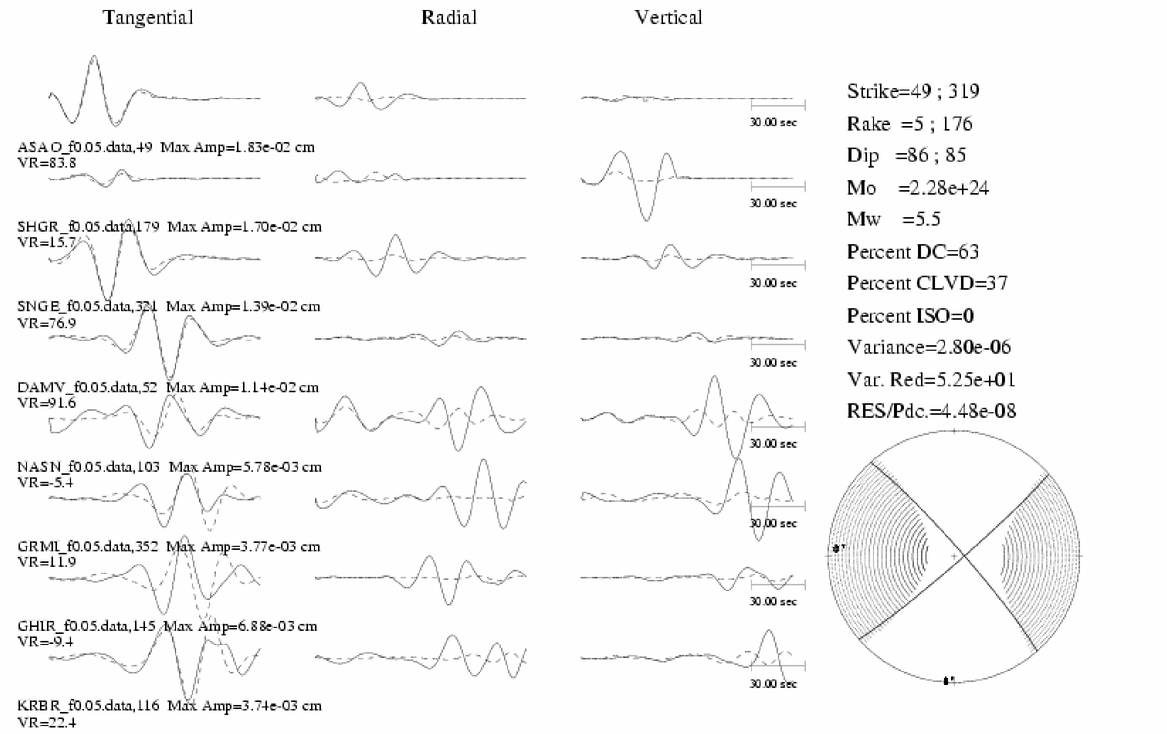

Figure 5. Moment tensor inversion results for the foreshock, 2006-03-30_19:36 (for other parameters see the caption of figure 2.).

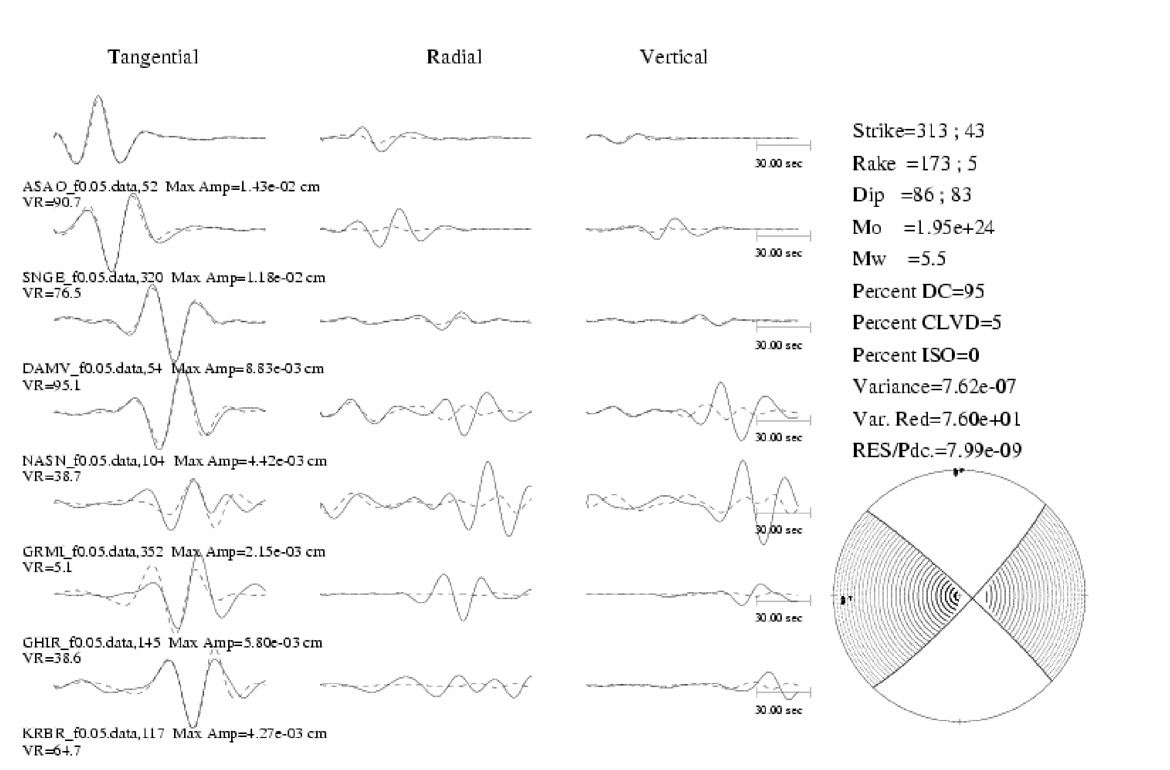

Figure 6. Moment tensor inversion results for the aftershock, 2006-03-31_11:54 (for other parameters see the caption of figure 2.).

6 DEPTH ESTIMATION

We considered different methods to determine the focal depth. The “optimal” focal depth was determined as the solution with maximum variance (data-model misfit) reduction which was found by repeating the inversion for different trial depth values (from 5 to 50km). Another measure which is useful for determining source depth in regions where explosive events are unlikely is the Var/Pdc ratio, which is the variance divided by the percentage of double-couple in the solution. Dividing the variance by the percentage of double-couple tends to deepen the minimum (e.g. Dreger and Helmberger, 1990). The depth estimation measures of the mainshock, 2006-03-31_01:17 are depicted in figure 7. Note that the focal mechanisms do not change significantly for different trial depth values and are quite stable. The variance reduction measure does not show a significant maximum for different depth values, while a clear maximum can be seen in Var/Pdc for this earthquake. The variation of Var/Pdc as function of depth is shown for all studied earthquakes in figure 8. As illustrated in the figure Var/Pdc variations as a function of depth do not provide a distinct maximum associated with the other events. This can be partly explained by of our choice of band pass filter. We tried different filters but different frequency bands degrade the results because of signal to noise considerations and the effect of structural complexity on higher frequencies. The overall waveform fitting at some stations was sensitive to changes in focal depth (e.g. station GRMI of event 2006-03-30_19:36).

7 DISCUSSIONS AND CONCLUSIONS

Focal mechanism of the M_w 6.5 March 31, 2006 Silakhor earthquake, the two largest foreshocks and a major aftershock in western Iran were determined using a weighted linear least squares moment tensor inversion in the time-domain. The inversion results based on broadband data from seismic stations in Iran showed stable results comparable with, but more internally coherent than, other independent solutions, despite the limited azimuthal coverage when only the Iranian stations are used. The fault planes determined coincide with the NW trend of pre-existing faulting in the area, notably the Zagros Main Recent Fault where geological evidence indicates dominant strike-slip characteristics. In general the misfit between the tangential observed data and model response was small. The fit for the vertical and radial components varied from case to case, presumably as a result of the greater sensitivity of these components to scattering from sub-horizontal boundaries. A relatively large CLVD component was indicated by the data. Especially for the mainshock, 2006-03-31_01:17, it is likely that this is simply a result of approximations inherent in the analysis, primarily that of using a one dimensional average Earth model in this tectonically active and complex area. Our estimates of the focal depths indicate that the brittle crust is limited to about less than 20km depth. Our results are in good agreement with the study of Pakzad and Mirzaei (2008) based on linear moment tensor inversion method.

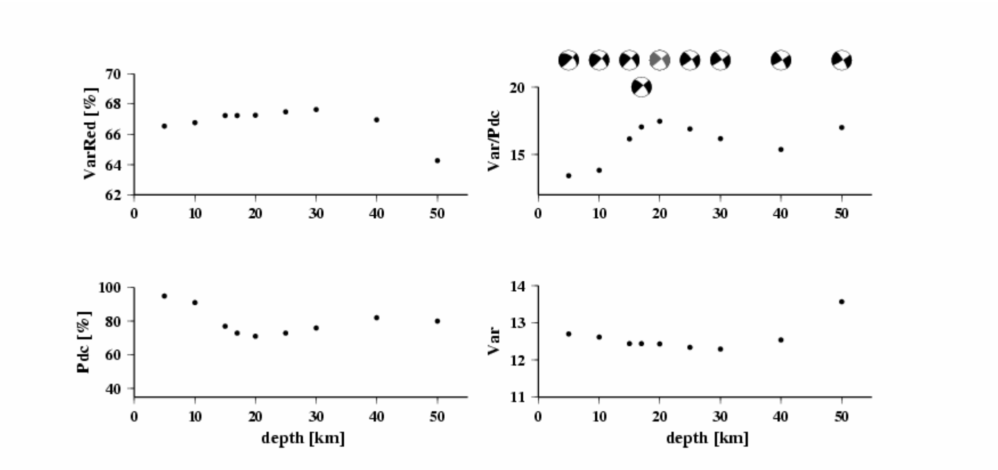

Figure 7. The variations of percentage of double-couple (Pdc), variance (Var), percentage of variance reduction (VarRed) and the variance divided by the percent double-couple (Var/Pdc) as a function of source depth for the main shock,2006-03-31_01:17, case I. For each inversion the Green's function alignment parameter has been optimised. The optimal solution is denoted by grey colour.

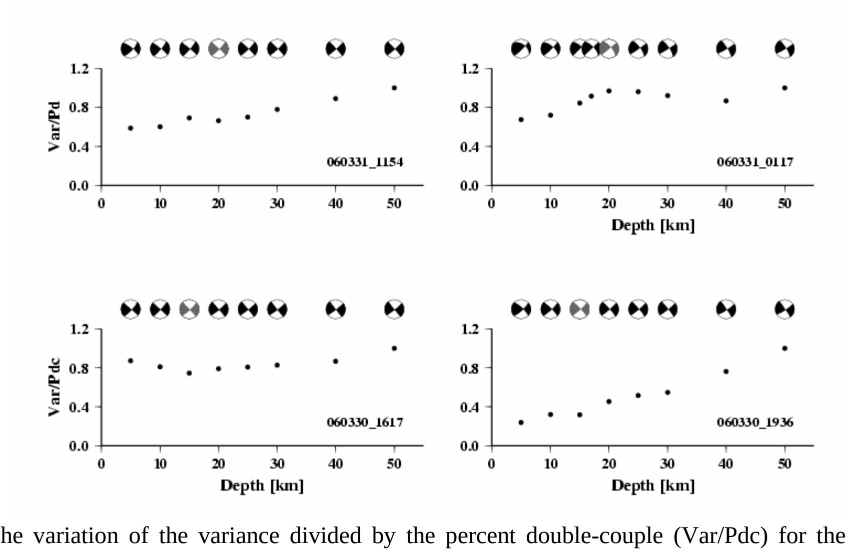

Figure 8. The variation of the variance divided by the percent double-couple (Var/Pdc) for the events studied. The optimal solutions are denoted by grey colour.

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