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ANALYSIS OF SOME AFTERSHOCKS OF THE RUDBAR EARTHQUAKE OF 1990 USING MASTER EVENT TECHNIQUE

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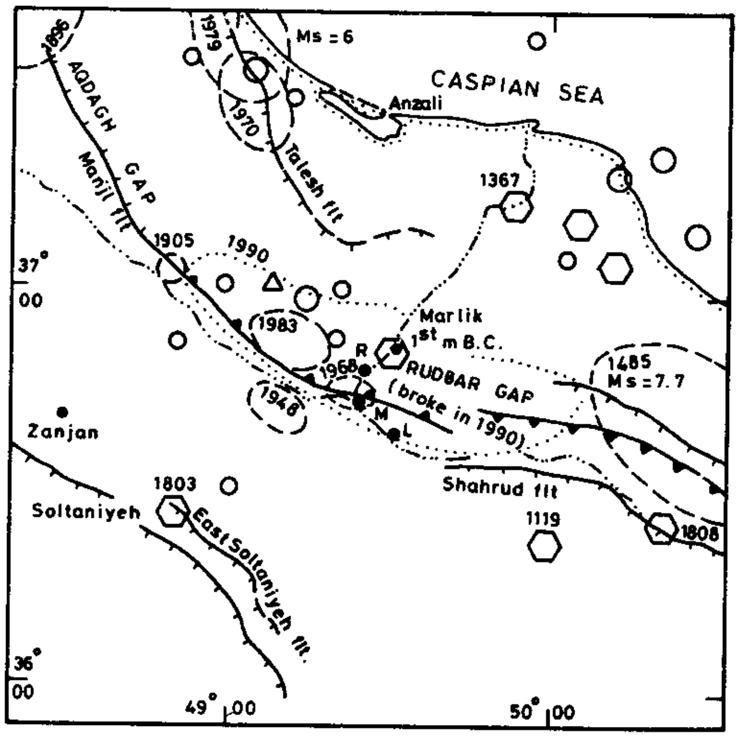
ABSTRACT

The seismograms recorded by a network of five seismograph stations operated by Institute of Geophysics, Teheran University, following the main Rudbar earthquake of June 20, 1990 were examined for a three week period from July 5, 1990, to July 22, 1990.

The arrival times of P-waves for 36 aftershocks were read with the utmost care. The first arriving P-wave was a direct wave from the hypocentre to each of the recording stations for 23 of these aftershocks. The first P-wave was a head wave at some of the recording stations for remaining 13 aftershocks . The data was used to locate the hypocentres of all 36 aftershocks with a computer program based on the master event technique. The 36 epicentres define a narrow belt oriented along an azimuth of N125° . The epicentre of the main Rudbar earthquake, as estimated by Institute of Geophysics, Teheran University, lies at the southern edge of this belt. The estimated focal depths were between 1.0 km and 16.0 km. The depth section perpendicular to the strike of the epicentral belt shows the hypocentres in a narrow subvertical zone. The depth section along the strike of epicentral belt shows the hypocentres aligned in a narrow zone dipping approximately 45° to the ESE.

The 95% confidence ellipses for the epicentres had major and minor axes of 16 km and 10 km. respectively in the worst case and 0.4 km and 0.2 km respectively in the best case. The esitmate of uncertainity in depth was ± 2 km. in the worst case and ± 0.2 kms in the best case.

Forty six first P-motion data for the more reliably located aftershocks yielded a fault plane solution consistent with that of the main Rudbar earthquake, as determined by Institute of Geophysics, Teheran University.



Seismotectonic map of the area around Rudbar (marked R in the centre of the Figure). The triangle NW of Rudbar is the NEIC Location of the foreshock of April 2, 1990, two months prior to main Rudbar shock of June 20, 1990. The meizoseismal zone is marked by dotted area. Historical earthquakes are shown by hexagons and recent ones by circles, with varying varying for magnitudes ranging from 7.0-4.0. Historical seismicity in Aqdagh gap is low and the pre-1990 recent earthquakes could be long-term precursors for the 1990 mainshock. (Adopted from Berberian et al., 1992).

INTRODUCTION

The phenomena of earthquakes is almost as ancient as the history of the earth; yet most available information about occurrence of ancient earthquakes in specific regions of the world are unscientific, incomplete and inaccurate. Such unreliable information about seismicity has often led to inaccurate assessments of the seismic potential of a region. This is true to a large extent in the context of Iran also.

In 1909, De Ballore (See Ambraseys, 1968) had envisaged that the area was inactive with complete absence of earthquakes in the Zagros mountains and in Luristan. Fifty years later, Gutenberg and Richter (1954), on the basis of maps exhibiting geographical distribution of epicentres of instrumentally recorded shallow, intermediate and deep focus earthquakes of large magnitude, could reliably conclude that (i) the Alpide-Himalayan belt passes through Iran, (ii) the belt was broadest in this part and (iii) several large earthquakes of shallow and intermediate depth had occurred there. Through concerted efforts of dedicated earth scientists who delved into ancient Arabic and Persian writings and others who helped set up sophisticated seismograph arrays in Iran, a reasonably accurate visualization of the pattern of seismic activity of the region has now emerged. Scientists are today aware that the Iranian plateau is one of the more seismically active areas of the world and that several catastrophic earthquakes occurred in Iran through the centuries. In the twentieth century alone destruction from such earthquakes have resulted in loss of at least 115,000 hundred lives here (Ambraseys, 1968; Berberian et al. 1992).

THE 1990 RUDBAR EARTHQUAKE

Recently, on June 20, 1990, at around midnight (00:30:38 local time), another major earthquake ($M_S = 7.7$, $M_W = 7.3$) occurred near Rudbar in NW Iran. It is the largest earthquake of this century to have greatly affected an urban area of Iran, devastating completely the cities of Rudbar, Manjil and Loshan besides nearly 700 villages in the Sefidrud and Shahrud river valleys. According to published reports, this earthquake alone has killed over 40,000 people, injured 60,000 and left more than 5,00,000 homeless.

The Rudbar earthquake occurred in the western section of the Alborz mountain belt. The seismic pattern of the region is discontinuous with several possible seismic gaps. A large seismic gap, the Rudbar - Aqdagh gap, separating the epicentral regions of the August 15, 1485 ($M_S = 6.5$) earthquake and that of the January 4, 1896 ($M_S = 7.7$) earthquake is identified in the region (Fig.1). Several moderate sized earthquakes (e.g. the earthquakes of January 9, 1905 ($M_S = 6.2$), June 17, 1948 ($m_b = 5.5$), August 12, 1968 ($m_s = 4.7$) January 19, 1970 ($m_b = 4.5$), July 22, 1983 ($m_b = 5.6$) and April 20, 1990 ($m_b = 3.7$)) (Fig.1) have been reported to have occurred here during the twentieth century (Berberian, et al. 1992). In a regional context the Rudbar earthquake possibly ruptured the eastern end of this seismic gap.

Thus the seismic potential of the western part of the Rudbar - Aqdagh gap should be treated with greater concern today. This is especially so because the Rudbar area has been recognized as a region of high seismic hazard in the seismic zoning map of Iran and in the Iranian code of Seismic Resistant Design of Buildings.

Aftershocks of the Rudbar Earthquake

A large earthquake never occurs in isolation. It is generally preceeded by some forshocks and almost certainly followed by numerous aftershocks. Aftershocks are an important source of information for understanding the mechanism of the main shock. Studies of aftershock sequences can provide information regarding (i) the faulting associated with the mainshock, (ii) long term re-distribution of stresses in the aftershock zone as also physical properties of crust and upper mantle material (Page, 1968). Since aftershocks are generally confined to the earth's crust and often specifically to its upper layers, large uncertainities in instrumental determination of their location parameters are common. However deployment of portable sensitive seismographs in the epicentral region of the main shock and usage of seismic phase data available from close-in seismographs increases the accuracy of these determinations (Mc Evilly, 1966; Page, 1968).

The Rudbar earthquake was followed by intense aftershock activity continuing for more than 5 months. A portable seismograph array, comprising of five high gain, short period seismometers, was operated during the period July 3, 1990 to September 3, 1990 by the Institute of Geophysics, Teheran University, at Gilavan, Dafraz, Siamazgi, Jirandehand and Loshan (Fig.2). The seismic array enclosing an area of 2400 km^2 , is located in the Alborz mountain region, in the Sefidrud river valley, straddling the epicentral region of the main Rudbar earthquake of June 20, 1990. The site of the Sefidrud reservoir and dam lies within the array.

Numerous aftershocks of the Rudbar earthquake have been recorded by this array. We report in this article the results of a detailed seismological analysis of a selected thirty-six of these, recorded during the period July 5-22, 1990.

ESTIMATION OF HYPOCENTRAL PARAMETERS OF THESE THIRTY SIX AFTERSHOCKS

Conventionally hypocentral location parameters of an earthquake are estimated from measurements of the arrival times of its various seismic phases to the different recording stations of the seismic network. Several algorithms, generally based on Geiger's (1912) method of least square optimization of absolute arrival time residuals, are easily available in the literature, (Bolt, 1960; Flinn, 1960; Lee and Lahr, 1975; Crosson, 1976; Spencer and Gubbin 1980; Sarkar et al., 1984; Ruud, 1990; Cassidy et al 1990, etc.).

A major disadvantage of all these conventional procedures is that unavoidable errors in arrival time data and irregular station distribution with respect to the earthquake epicentre often lead to large standard errors in the estimates, indicating the presence of large uncertainities in the absolute location of the hypocentre.

Master Event Technique

The master event technique estimates relative location of the earthquake hypocentre and is an useful alternative to these conventional techniques. In this scheme, it is assumed that the hypocentral parameters of a master seismic event and the arrival times of its seismic phases to all the recording stations of the array are known a priori and are error-free. The observed data set consists of arrival times of seismic phases of both the master event and the investigated earthquake (henceforth referred to as the secondary event) to the various recording stations of the seismic array. The procedure is to optimize, in a least square sense, relative arrival time residuals from the secondary event with respect to those from the master event. Thus here, the hypocentral parameters of the secondary event relative to those of the master event are estimated. Also the estimated standard errors of location signify uncertainities in the relative location of the secondary hypocentre with respect to the master hypocentre. Since the standard errors of location are smaller in this latter technique, a more reliable three dimensional visualization of the mutual spatial relationship amongst the hypocentres of the investigated secondary seismic events and the master seismic event is obtained. It thus seems appropriate to use a master event technique rather than the conventional techniques for reliable location of aftershock hypocentres.

Selection of Master Event

Usually, while locating aftershock hypocentres by the master event technique, the main shock is chosen as the master event. However, in the present study, it was not possible to use the main Rudbar earthquake of June 20, 1990, as the master event for the following reason. Since the seismic array (Fig.2) was not in operation during June 1990 when the main earthquake occurred, arrival time data of various seismic phases of the main shock to the different seismograph stations of this array, a pre-requisite of the master event scheme, were not available.

Again, although the aftershocks considered in this study are probably second order in nature, we could not use their main shock as the master event, for the following reason. Several large aftershocks have been recorded during the period July 3 to July 23, 1990 by our seismograph array (Fig.2) and their hypocentres estimated by Institute of Geophysics, Teheran University (IGTU), Iran, (Rezapoor, 1991). No estimates of magnitudes are given for the listed aftershocks which occurred in the period July 5, 1990 to July 7, 1990 (Rezapoor, 1991). The estimated epicentres of a few of these listed earthquakes, occurring during July 5-7, 1990, lie within the seismograph array and are possibly the primary shocks of the aftershocks investigated by us in this study. However, the local recordings of these larger shocks do not provide clear, unambiguous P-phase arrival time data on the seismograms available to us and hence could not be used as master events.

To recompense, we chose a synthetic master event for our study. The choice of the hypocentral coordinates of this synthetic event is based on the following reasoning. The epicentre of this synthetic master event $(36.81^{o}N,\ 49.50^{0}E)$ has been so selected as to lie in the center of the array. This is to increase the reliability of the relative locations of the aftershocks, especially those which lie within the array. It is noteworthy that a large aftershock which occurred on July 5, 1990, at 18 hours 59 min 50.70 sec, has been located

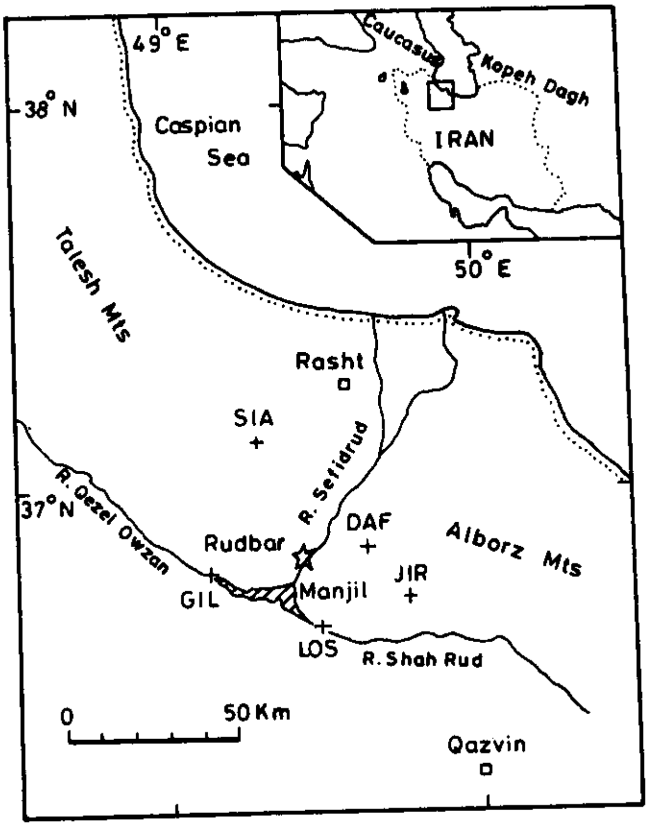


Fig. 2 Map showing locations of seismograph stations of the_array (marked by +). The NEIC location of the main Rudbar earthquake (merked with star) and the site of the Sefidrud reservoir and dam (hatched area) are also shown.

at ((36.81° N, 49.50° E, 1.32 km) by IGTU (Rezapoor, 1991). Since most of the large and moderate earthquakes of the region are shallow focus, the depth of the synthetic earthquake was chosen to be 10 km below mean sea level.

The Seismic Velocity Model

The computational procedure also requires a suitable model for the subsurface structure of the region. On the basis of travel time residuals of earthquakes occurring in the Iranian plateau, Akasheh (1975) has proposed a seismic velocity model having uniform crustal thickness of 45 km and crustal P-wave velocity ranging from 4.6 km/s to 6 km/s. We therefore assumed a homogeneous half space seismic velocity model with constant P-wave velocity of 5.0 km/s for our computations.

RESULTS

Aftershock Epicentres

Fig. 3 gives a visual depiction of the distribution of the 36 aftershock epicentres determined by us and the main Rudbar epicentre determined by IGTU. The 36 epicentres define a belt, 64 km long, 7 km wide and generally oriented WNW-ESE . A majority of the earthquakes lie close to Dafraz (DAF). A few earthquakes on the SE flank of the belt lie close to Jirandeh (JIR) while a few others on the NW side appear to lie on a line which is roughly oriented as the perpendicular bisector of the line joining Gilavan (GIL) and Dafraz (DAF).

Aftershock focal depths

The estimated focal depths of the 36 earthquakes lie within the top 20 km of the local crust with 80% of them lying within 12 km below mean sea level.

Reliability of the hypocentral parameter estimates

The reliability of the hypocentral parameter estimates can be discussed on the basis of estimates of the area of the joint confidence region and also relative standard errors for the four hypocentral parameters. We estimated these statistical parameters assuming that the arrival time residuals of the direct P-phases to the different seismograph station were random variables, normally distributed with zero mean and variance σ^2, common to all these staions. It was found that the area of the confidence ellipse for the epicentres was of the order of 1.5 km^2 and the relative standard errors for the epicentral coordinate estimates were of the order of 0.1 km respectively for the 23 earthquakes lying in the central part of the belt. These were of the order 10.0 km^2 and 0.7 km respectively for the 13 earthquakes lying on NW and SE flanks of this central part showing that the values are far less for the former 23 earthquakes than for the latter 13 earthquakes. This is mainly due to the proximity of the synthetic master event hypocentre to the central cluster of 23 aftershocks. Also the fact that the earthquakes of the central cluster are nearer the center of the seismograph array

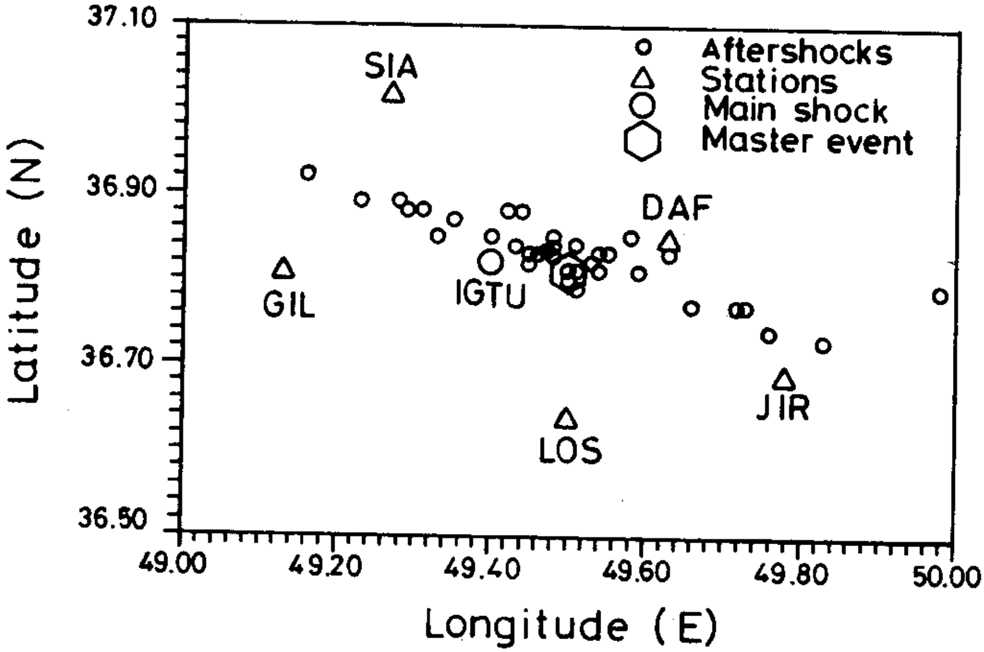


Fig. 3 Epicentral map of the thirty six aftershocks reported in this study. The epicentre of the main Rudbar shock as located by Institute if Geophysics, Teheran University (IGTU) is also shown.

and that their arrival time data were more accurate allows us to infer that the epicentral estimates of these 23 aftershocks are most reliable.

The first arrivals at all the recording stations for each earthquake have been assumed to be direct P-phases. However for some of the 13 earthquakes, occurring on the NW and SE flank of the epicentral belt, the first arrivals at some of the stations may be possibly of the head wave type. In a homogeneous half space model such erroneous assumptions generally lead to a trade off between greater depth estimate and lesser epicentral distance. This is applicable for the six aftershocks occurring close to JIR station. In the case of the seven aftershocks occurring near SIA and GIL, however, some stronger constraints to epicentral locations were provided, because of equal proximity of these two stations (SIA and GIL) from these earthquakes. Also for these latter aftershocks only JIR possibly recorded first arrivals as head waves. We thus opine that the seven aftershock epicentres near the NW flank of the epicentral belt are nearly as reliable as those in the central part of the belt although their focal depths are not as reliable in comparison. The focal depth estimates of the aftershocks lying in the central part are most reliable.

Depth Sections

Depth sections along two mutually perpendicular vertical planes, striking parallel (WNW-ESE) and transverse (NNE-SSW) to the strike of the epicentral belt are displayed in Figs. 4a and 4b.

Fig. 4a shows that most of the earthquakes lie in the (6.0-12.5)km depth range with only one earthquake occurring below 14 km depth. The projected hypocentres appear to lie in a 14 km wide zone dipping roughly $48^o - 50^o$ to the ESE side.

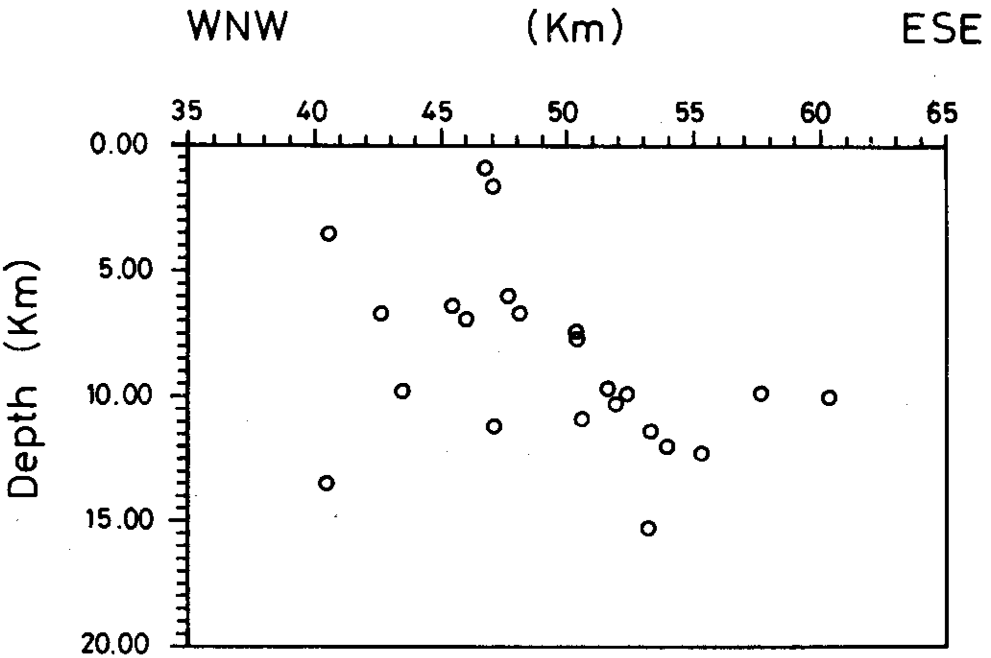
Fig. 4b shows that most of the earthquakes lie in a near vertical zone (8.0-9.0)km wide and less than 14 km thick. The earthquake hypocentres appear to lie along parallel planes dipping $75^o - 80^o$ to SSW direction.

Aftershock Magnitudes

The code magnitudes of the aftershocks is estimated (Tsukuda et al.,1991) to be in the range 3.0 - 4.0.

Composite fault plane solution

The composite fault plane solution (Fig.5) is based on only 46 highly reliable first P-motion data from the 23 earthquake hypocentres lying in the central part of the seismic belt. These are plotted on an equal area projection of the lower half of the focal sphere for determining a composite fault plane solution. Since the aftershock hypocentres are clustered in a small volume of the upper crust, the polarity data for the different recording stations generally lie clustered in small zones on the equal area net and do not provide strong constraints for the nodal planes. As a result several fault plane solutions appear permissible. The range covers oblique-slip on steeply dipping reverse/normal faults to sinistral strike slip on subvertical moderately dipping faults. Eight prominent solutions, satisfying the first motion



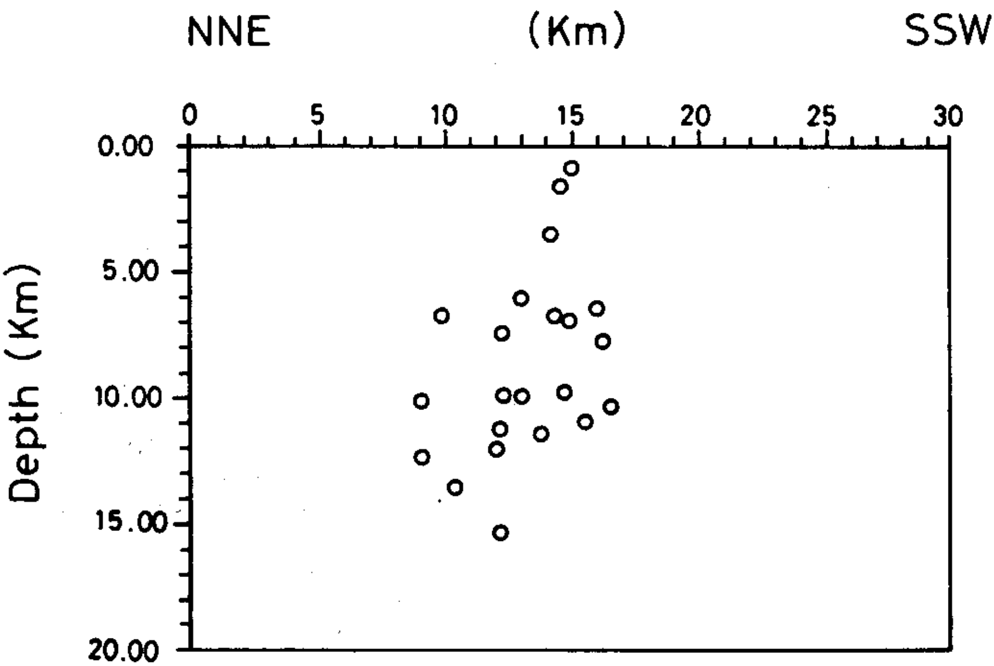


Fig. 4 Depth sections (a) along and (b) transverse to the strike of the epicentral belt.

observations, are listed below in Table I. In all solutions, there are about 7 to 10 inconsistencies.

Table I Numerical data for the various composite focal mechanism solutions which satisfy the first-motion data for 23 aftershocks.

Solution	NP1				NP2			
No.	Strike	Dip	Dip Dire	Slip	Strike	Dip	Dip Dire	Slip
1	230	70	NW	180	140	90	SW	-10
2	230	70	SE	180	137	90	SW	-10
3	50	90	SE	180	320	90	NE	0
4	229	54	NW	180	320	90	NE	-36
5	50	34	SE	18	156	80	SW	56
6	50	34	SE	172	316	86	NE	56
7	34	80	SE	178	125	88	SW	10
8	32	50	SE	174	125	88	SW	40

Our preference is for solution 8 (Fig.5) with the nodal plane having $N125^o$ strike, steep dip to the SSW and oblique left lateral motion, as the fault plane. This is because of the following reasons. (i) Field observations reveal surface faulting due to the Rudbar earthquake along three main discontinuous complex fault segments. It has been reported on the basis of geological and geophysical investigations that each of these fault segments has strike ranging from 95^o - 120°, oblique left-lateral reverse motion and are subvertical or have steep dips to S or SSW (Berberian et al., 1992) (ii) Also the dip of NP1 is in conformity with the dip of the earthquake zone in the depth section of Fig4a.

DISCUSSION

Comparison of The Estimated Hypocentre Locations of the Rudbar Earthquake and the 23 Aftershocks.

Epicentral Locations

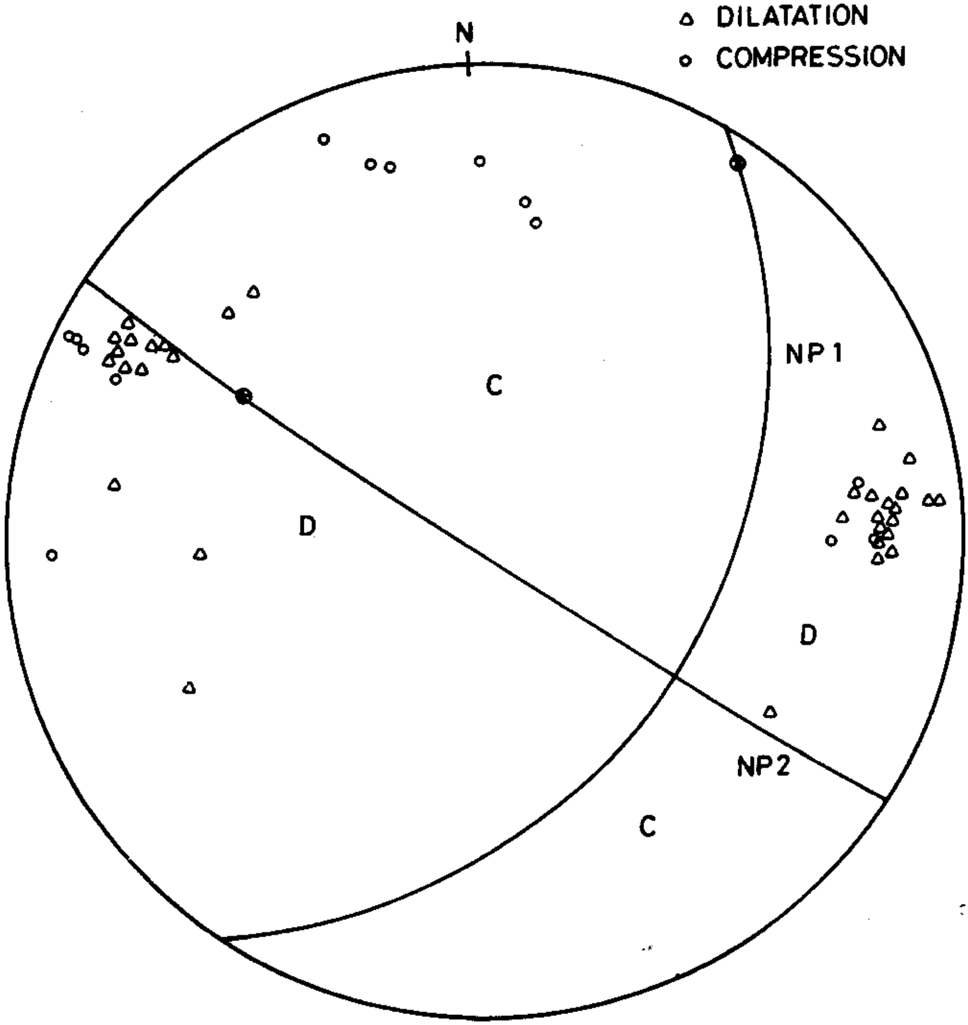


Fig. 5 A lower hemisphere equal area plot of the available first motion data for the aftershocks. Nodal planes corresponding to solution 8 of Table 1 are shown. Compressional and dilatational quadrants are identified by C and D respectively. Nodel plane NP1 is the prefered plane for reasons discussed in text.

The main shock epicentre should be within the rupture zone defined by the aftershock epicentres. We opine that the aftershocks investigated by us are of second order; that is, they do not possibly belong to the main Rudbar earthquake but are associated with some large aftershock of the Rudbar earthquake. The epicentral location of the main Rudbar earthquake is estimated by IGTU to be at $38.82^o N$,$49.40^o E$ This lies at the southwestern end of the epicentral belt defined by the 36 aftershocks of our study (Fig.3). Also epicentres of four large aftershocks, occuring during July 5 to July 22, 1990 recorded by USGS and located by the IGTU are estimated to lie within the same epicentral belt (Rezapoor, 1991). Thus although our data set consists of only a limited number of the numerous, second order aftershocks recorded by the seismograph network operating during the period July 3, 1990 to September 3, 1990, it is obvious that several large aftershocks and also possibly the main Rudbar shock lie in this same epicentral belt. This can be said with confidence especially because the epicentres of several large and small aftershocks of the Rudbar earthquake reported by Rezapoor (1991) have been estimated using local arrival time data from the same seismograph network, so that their relative epicentral locations must be of great accuracy.

The 36 representative second order aftershocks of the region define a rupture zone approximately 150 km^2 in area. This corresponds with a main shock of magnitude 6.5 (Kasahara, 1981). Thus although no magnitude was estimated for the larger aftershocks, recorded during July 5-7, 1990 (Rezápoor, 1991), our data seems to imply that at least some of these have magnitude of the order of 6.0 to 6.5.

Focal depths

The focal depth of the Rudbar earthquake estimated from centroid moment tensor solution is 14 km. Seismologically determined slip suggest that the main rupture went deeper than 15 km. However, several large aftershocks at focal depth less than 14 km are also reported e.g. the aftershock of 24 June, 1990 has a centroid moment tensor depth of 8 km. Most of the aftershocks listed in our study lie within 14 km depth. Thus there appears conformity in the estimated depths of the aftershocks investigated in our study with those estimated from other studies for other aftershocks of the region.

Comparison of composite fault plane solution for the 23 aftershocks with those of Rudbar earthquake and other large aftershocks of the area.

Berberian et al. (1992) reported the focal mechanism of the Rudbar main shock from an inversion of broad band body waves recorded by GDSN and CDSN. They opine that the main shock rupture was complex with at least 3 subevents in the first 20 seconds. The double couple solution for the major event has strike 292^o , dip 88^o and rake -90^o. Also the observed surface faulting in the area showed a strike of $275^o - 300^o$ (Berberian et al,1992).

Berberian et al.(1992) also determined focal mechanism of two aftershocks using joint inversion of regional and teleseismic body waves. The first aftershock occurring 12 hours after the main Rudbar shock was the largest and was located at $36.64^o N$,$49.8^o E$, ESE of Rudbar. It caused additional damage and landslides in the epicentral region. The focal mechanism involved thrusting (st-ike 026° ,dip 69°, rake 87°). The second aftershock occurred on 24 June, 1990, NNE of Rudbar and caused landslides and road-blockades. The earthquake had a mechanism (strike 235° , dip 70° , rake −164°) similar to the main shock.

The mechanism of our chosen fault plane solution is in conformity with the mechanism proposed by Berberian et al. (1992) for the main Rudbar earthquake. The nodal plane chosen by us from our composite fault plane solution has approximately the same orientation as the preferred nodal plane of the Rudbar earthquake and the June 24, 1990 aftershock.

No fault plane solution is available for any of the large aftershocks occurring during July 5-7, 1990, (Rezapoor, 1991) and so no comparison is possible with these aftershock mechanism.

CONCLUSION

The results based on a detailed analysis of 36 selected second order aftershocks of the Rudbar earthquake of June 20, 1990 define a 64 km long, 7km wide epicentral belt, oriented WNW-ESE. The depth sections show that 50% of the earthquakes lie within the top 12 km of the upper crust. The preferred composite fault plane solution exhibits oblique, left-lateral motion.

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