Earthquake Potential in the Zagros Region, Iran

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Abstract

Seismic strain and b value are used to quantify seismic potential in the Zagros region (Iran). Small b values (0.69 and 0.69) are related to large seismic moment rates (9.96×10^{17} and 4.12×10^{17}) in southern zones of the Zagros, indicating more frequent large earthquakes. Medium to large b values (0.72 and 0.92) are related to small seismic moment rates (2.94×10^{16} and 6.80×10^{16}) in middle zones of the Zagros, indicating less frequent large earthquakes. Small b value (0.64) is related to medium seismic moment rate (1.38×10^{17}) in middle to northern zone of the Zagros, indicating frequent large earthquakes. Large b value (0.87) is related to large seismic moment rate (2.29×10^{17}) in northwestern zone, indicating more frequent large earthquakes. Recurrence intervals of large earthquakes ($M > 6$) are short in southern (10 and 14 years) and northwestern (13 years) zones, while the recurrence intervals are long in the middle (46 and 114 years) and middle to northern (25 years) zones.

Key words: seismic strain, moment tensor, Zagros, b value, recurrence interval.

1. INTRODUCTION

The Zagros tectonic province is formed due to continuous convergence between the continental Arabian plate with the continental microplates of Central Iran since the Miocene to the present (Agard *et al.* 2005, Alavi 1994,

Kadinsky-Cade and Barazangi 1982) (Fig. 1). The present velocity of Arabia with respect to Eurasia increases from west to east along the Persian Gulf from 18 to 25 mm yr⁻¹, oriented about N10°E (Sella *et al.* 2002, Walpersdorf *et al.* 2006). Roughly half of this convergence between Arabian plate and Eurasian plate is accommodated by crustal shortening, thrusting and folding in the Zagros (*e.g.*, Vernant *et al.* 2004). Earthquake focal mechanism solutions demonstrate shortening and thickening through major thrust faults, responsible for deformation in the Zagros (*e.g.*, Mostafazadeh *et al.* 2000, Talebian and Jackson 2004). Because of evaporate ductile layers in sedimentary part of the crust, no coseismic surface rupture is observed in this region (Walker *et al.* 2005). On the other hand, there are several visible folds in the Zagros (*e.g.*, Baker *et al.* 1993, Berberian 1995, McQuarrie 2004).

On the basis of rate and state of deformation deduced from GPS surveys, the Zagros has been divided into two parts (the North Zagros and the Central Zagros) (Fig. 1). Right lateral strike slip Kazerun Fault (Baker *et al.* 1993) is

Fig. 1. Location and topography map of the Zagros region. KF: Kazerun Fault. The right lateral strike slip Kazerun Fault is considered as the border between the North Zagros and Central Zagros (Walpersdorf *et al.* 2006).

considered as the border between the North Zagros and Central Zagros (Vernant *et al.* 2004, Walpersdorf *et al.* 2006). In the North Zagros, present deformation is composed of a $3\text{--}6\text{ mm yr}^{-1}$ shortening perpendicular to the Zagros strike, and a $4\text{--}6\text{ mm yr}^{-1}$ strike slip motion parallel to the Zagros strike. In the Central Zagros, the present deformation is only the shortening of $8 \pm 2\text{ mm yr}^{-1}$, perpendicular to the Zagros strike (Walpersdorf *et al.* 2006). Large portion of the deformation is observed in southern part of the Zagros, while seismicity is more widely spread all over the region. Accordingly, it is believe that evaporate ductile layers decouple the surface sedimentary layers from the seismogenic basement (*e.g.*, McQuarrie 2004). Therefore, the shallow deformation which is observed by GPS is related to the deformation of the sedimentary cover and does not represent the basement deformation (Walpersdorf *et al.* 2006). Seismic strain of the Zagros has been investigated as well (Jackson and McKenzie 1988, Ekstrom and England 1989, Jackson *et al.* 1995, Masson *et al.* 2005). Jackson and McKenzie (1988) used large earthquakes ($M_s \geq 6.0$) in the time interval from 1908 to 1981. They estimated maximum velocity values at 3.83 , 1.34 , and 0.16 mm yr^{-1} in $S40^\circ E$, $N50^\circ E$ and Up directions, respectively. Only 10 per cent of the total deformation in Zagros is released by earthquakes (Jackson and McKenzie 1988). In fact, most of the Zagros deformation is aseismic (Jackson *et al.* 1995, Masson *et al.* 2005). Masson *et al.* (2005) divided the Zagros into 6 triangular regions and used earthquakes in time interval from 1909 to 2002 to calculate ratio of the seismic strain to the geodetic strain. The ratio is 2-3 per cent in the North Zagros, while the ratio is 4-22 per cent in the Central Zagros (Masson *et al.* 2005).

Parameter b value is the slope of frequency-magnitude distribution ($\log_{10} N = a - bM$), where b value reveals the ratio of number of smaller to larger earthquakes (Gutenberg and Richter 1954). N is the number of events with magnitude larger or equal to M and a is a constant. The equation is applicable to a homogeneous and complete catalog in which magnitude of completeness is constant during time span of the catalog. Spatial distribution of b value is very heterogeneous and it can be observed even from 1 to 30 km (*e.g.*, Wiemer *et al.* 1998, Wyss *et al.* 2004) which may be due to heterogeneity in material properties of the source region (Mogi 1962) and stress distribution (Scholz 1968). The b value often varies in the range of 0.60 to 1.30 in different areas with different tectonic regimes (*e.g.*, Frohlich and Davis 1993). Higher b values have been observed in areas in which smaller earthquakes are more frequent than larger ones, whereas lower b values are estimated in areas in which larger earthquakes are abundant (Gutenberg and Richter 1944). Since large number of small earthquakes is characteristic of regions of low strength and large heterogeneity in the crust materials, higher b values are corresponding to this kind of regions. On the other hand, lower

b values are expected in homogeneous and resistant regions (Mogi 1962, Tsapanos 1990). High b values are also observed in regions with decreased shear stress (Urbancic *et al.* 1992) and extensional stress (Frohlich and Davis 1993). In contrast, low b values are related to increased shear stress or effective stress, and higher seismic moment release (Scholz 1968, Wyss 1973). Moreover, thrust zones have b value smaller than 1, strike-slip zones have b value around 1 and normal faulting is associated with b value larger than 1 (Schorlemmer *et al.* 2005). In this paper, seismic strain and b values are studied during 1963-2016 in the Zagros region. Finally, earthquake potential in the Zagros region is evaluated by means of the seismic strain rates and b values.

2. DATA SET

Data of Harvard Global Centroid Moment Tensor catalog (GCMT 2015) and those obtained by several authors (Ekstrom and England 1989, Baker 1993, Baker *et al.* 1993, Maggi *et al.* 2000, Talebian and Jackson 2004, Ashkpour and Mostafazadeh 2008) for earthquakes with moment magnitude $M_w \geq 4.8$ in time interval from January 1963 to January 2016 are used to deduce the seismic strain in the studied region (Fig. 2 and Appendix).

To estimate b value we prepared a data set for the Zagros consisting two parts. The first part was compiled from the International Seismological Center (ISC; <http://www.isc.ac.uk>) bulletin between January 1963 and January 2016 (hereafter called ISC part). The second part was compiled from the Iranian Seismological Center (IRSC; <http://irsc.ut.ac.ir/bulletin.php>) data from January 2006 to January 2016 (hereafter called IRSC part). IRSC has published local catalog of events which have occurred since January 2006. We removed earthquakes from IRSC part which are reported in ISC part simultaneously. To avoid heterogeneity in magnitude scales, we simply considered magnitude scales of events with $M \leq 5$ to be equal to moment magnitude M_w (Heaton and Kanamori 1984). For events with $M > 5$, corresponding relations for the Zagros (Shahvar *et al.* 2013) were applied to convert various magnitude scales to M_w . Therefore, magnitude scale of all events in our data set is homogenized to M_w . The final identical data set of the Zagros contains 22583 earthquakes during 1963-2016 with magnitude range of 0.4 to 6.9 (hereafter called original catalog of the Zagros).

Figure 3 shows the number of events which occurred during hours of the day for the original catalog of the Zagros. Ambient noise during daytime hours causes a decrease in the number of detected events during daytime hours. Numbers of events during daytime hours are not greater than the number of events during nighttime hours. Therefore, the original catalog of the Zagros is not contaminated by quarry and mine blasts (Gulia *et al.* 2012).

Fig. 2. Focal mechanisms (CMT catalog) of earthquakes with $M_w \geq 4.8$ occurred in time interval 1963-2016 which have been used to estimate the strain tensors in the Zagros region. Thrust faulting is dominant in the Zagros. Strike-slip faulting can also be observed in central and northwestern parts of the region.

Fig. 3. Number of events for hours of the day in the Zagros data set during 1963-2016.

Fig. 4. Variations and maximum value of completeness magnitude (M_c) during 1963-2016 in original catalog of the Zagros. The completeness magnitudes are estimated using maximum curvature method (Wiemer and Wyss 2000) and moving window approach with a window of 200 events, moved by 150 events. Dashed lines indicate one standard deviation from the average. The uncertainties in the completeness magnitudes (dashed lines) are obtained from $N = 200$ bootstrap samples.

Fig. 5. Epicenters of complete catalog of the Zagros region ($M_w \sim 4.7-6.9$) in time interval from 1963 to 2016 (ISC and IRSC bulletins). Based on distribution of earthquakes with $M \geq 5$ and type of faulting (see Fig. 2), the Zagros is divided into 6 zones to estimate strain tensors in time interval 1963-2016. Coordinates of the 6 zones are listed in Table 1. KF is Kazerun Fault which is considered as the border between the North Zagros and Central Zagros (see Fig. 1).

Variations of completeness magnitude (M_c) during 1963-2016 in original catalog of the Zagros can be seen in Fig. 4 which is prepared by means of ZMAP software (Wiemer 2001). The completeness magnitudes are estimated using maximum curvature method (Mignan and Woessner 2012, Wiemer and Wyss 2000, Woessner and Wiemer 2005). As Mignan and Woessner (2012) asserted, for a catalog in which M_c is not constant during time span of the catalog, the maximum value of M_c must be considered as M_c of the whole catalog. The maximum value of M_c is equal to 4.7 in the original catalog of the Zagros (Fig. 4). Accordingly, we removed events smaller than $M_c = 4.7$ to form complete catalog of the Zagros during 1963-2016. The complete catalog contains 972 earthquakes which are mapped in Fig. 5.

3. METHODS

3.1 Seismic strain

Strain tensor in volume V of the crust is defined as (Molnar 1983):

$$e_{ij} = \frac{1}{\mu V} \sum_{k=1}^N M_{ij}^k \quad (1)$$

where μ stands for the shear modulus or rigidity of the crustal rock ($\mu = 3.3 \times 10^{10}$ N/m²), N is the total number of events, and M_{ij} is the moment tensor of an earthquake:

$$M_{ij} = M_0 (n_i d_j) , \quad (2)$$

where M_0 is scalar moment of the earthquake; n , d are, respectively, the normal and slip vectors of the corresponding fault plane defined as (Pujol 2003):

$$n = \begin{pmatrix} \sin \delta \sin \phi \\ \sin \delta \cos \phi \\ \cos \delta \end{pmatrix} \quad (3)$$

$$d = \begin{pmatrix} -\cos \lambda \cos \phi - \sin \lambda \cos \delta \sin \phi \\ \cos \lambda \sin \phi - \sin \lambda \cos \delta \cos \phi \\ \sin \lambda \sin \delta \end{pmatrix} \quad (4)$$

where ϕ , δ , λ are strike, dip, and rake of the fault plane, respectively.

The asymmetric second rank strain tensor e_{ij} can be written as sum of symmetric (ε_{ij}) and anti-symmetric (ω_{ij}) tensors as follows:

$$e_{ij} = \varepsilon_{ij} + \omega_{ij} \quad (5)$$

where

$$\varepsilon_{ij} = \frac{1}{2}(e_{ij} + e_{ji}) \quad (6)$$

$$\omega_{ij} = \frac{1}{2}(e_{ij} - e_{ji}) \quad (7)$$

The ε_{ij} tensor contains dilatation and shear components of the strain, while the ω_{ij} tensor involves rotation components of the strain.

3.2 The b value

Assuming that the catalog can be divided into s subcatalogs with different magnitude of completeness, the likelihood function of seismicity parameters θ in the whole span of catalog is defined as product of likelihood functions of seismicity parameters in s subcatalogs (Kijko and Sellevoll 1989):

$$L(\theta|X) = \prod_{i=0}^s L_i(\theta|X_i) \quad (8)$$

where $\theta = (\beta, \lambda)$, β is related to b value as $b = \beta \log e$, and e is the Neperian number. λ is the earthquake activity rate, and X_i are magnitudes in the i -th subcatalog. If magnitude of earthquakes is independent of the earthquakes number, the likelihood function of seismicity parameters θ in i -th subcatalog can be written as a product of likelihood functions of parameters β and λ (i.e., $L_i(\theta|X_i) = L_{i\beta} \cdot L_{i\lambda}$); hence, Eq. 8 can be rewritten as:

$$L(\theta|X) = \prod_{i=0}^s L_{i\beta} \cdot L_{i\lambda} \quad (9)$$

Using the maximum likelihood method, the estimation of parameter β is accompanied with putting the first derivative of the likelihood function in terms of parameter β equal to zero:

$$\partial \ln L(\theta|X) / \partial \beta = 0 \quad (10)$$

3.3 Recurrence interval

Recurrence interval for earthquakes larger than M_w can be estimated from the b value and seismic moment rate as (Ward 1994):

$$T(M_w) = \left[\frac{b}{1.5 + b} \right] \frac{10^{(1.5+b)M_{\max} + 9.05}}{\dot{M}_{\text{seismic}} [10^{bM_{\max}} - 10^{bM_w}]} \quad (11)$$

where $M_{\max}$ stands for the maximum possible earthquake magnitude, and $\dot{M}_{\text{seismic}}$ represents seismic moment rate which is defined as:

$$\dot{M}_{\text{seismic}} = 2\mu A H_s \dot{\varepsilon}_{\max} \quad (12)$$

where μ is the rigidity (3×10^{10} N/m²), A represents the surface area over which strain release is distributed, H_s is thickness of the seismogenic layer,

and $\dot{\epsilon}_{\max}$ stands for the largest absolute eigenvalue of seismic strain rate tensor.

4. RESULTS AND DISCUSSION

4.1 Seismic strain

In order to estimate seismic strain of the Zagros in details, we divided the Zagros into 6 zones, based on type of faulting (Fig. 2) and distribution of earthquakes with $M \geq 5$ (Fig. 5). Coordinates of the 6 zones are listed in Table 1. According to previous authors (*e.g.*, Ekstrom and England 1989, Jackson and McKenzie 1988), the thickness of seismogenic layer in the Zagros is considered to be 15 km. Therefore, volume of each zone can be easily obtained by multiplying surface dimensions by the thickness of seismogenic layer (Table 1).

Table 1
Coordinates, thickness of seismogenic layer (H_s)
and volume of 6 zones in the Zagros (see Fig. 5)

Zone	Coordinates [degree]	H_s [km]	Volume [km ³]
1	53.50 , 28.40 56.80 , 28.40 56.80 , 26.90 53.50 , 26.90	15	804 710
2	51.95 , 29.75 53.70 , 28.30 52.70 , 27.40 50.90 , 28.95	15	491 530
3	51.70 , 30.50 52.30 , 30.00 51.20 , 29.20 50.60 , 29.70	15	165 960
4	50.00 , 31.30 51.25 , 30.20 50.70 , 29.80 49.40 , 30.90	15	176 740
5	49.00 , 32.20 51.10 , 32.20 51.10 , 31.40 49.00 , 31.40	15	262 730
6	46.90 , 33.80 49.10 , 33.80 49.10 , 32.40 46.90 , 32.40	15	473 010

Table 2

The asymmetric and symmetric strain tensors of 6 zones
in the Zagros in the time interval 1963-2016

Zone	e_{ij}			ε_{ij}		
1	-6.9E-07	1.4E-08	1.0E-6	-6.9E-07	2.8E-07	3.3E-07
	5.5E-07	3.8E-08	-1.2E-06	2.8E-07	3.8E-08	-6.2E-07
	-3.4E-07	1.6E-08	7.1E-07	3.3E-07	-6.2E-07	7.1E-07
2	-4.9E-07	2.6E-07	3.8E-07	-4.9E-07	3.8E-07	-1.8E-08
	5.0E-07	-9.8E-08	-5.7E-07	3.8E-07	-9.8E-08	-1.9E-07
	-4.1E-07	1.8E-07	4.7E-07	-1.8E-08	-1.9E-07	4.7E-07
3	-7.9E-08	4.3E-07	2.5E-07	-7.9E-08	2.4E-07	1.1E-07
	5.3E-08	2.8E-08	-2.4E-07	2.4E-07	2.8E-08	-1.5E-07
	-1.3E-08	-7.3E-08	6.0E-08	1.1E-07	-1.5E-07	6.0E-08
4	-8.8E-08	1.4E-07	9.4E-08	-8.8E-08	7.8E-08	3.2E-08
	1.5E-08	-3.4E-08	-8.5E-08	7.8E-08	-3.4E-08	5.1E-09
	-3.0E-08	9.5E-08	1.3E-07	3.2E-08	5.1E-09	1.3E-07
5	-1.4E-07	1.4E-08	3.9E-08	-1.4E-07	4.1E-08	6.3E-09
	6.9E-08	2.0E-07	-4.2E-07	4.1E-08	2.0E-07	-2.6E-07
	-2.6E-08	-9.9E-08	1.9E-07	6.3E-09	-2.6E-07	1.9E-07
6	-2.9E-07	2.2E-07	4.2E-07	-2.9E-07	1.5E-07	1.5E-07
	8.4E-08	-3.5E-08	-3.7E-07	1.5E-07	-3.5E-08	-1.5E-07
	-1.0E-07	7.2E-08	2.6E-07	1.5E-07	-1.5E-07	2.6E-07

Fault plane solution and scalar moment of earthquakes with $M \geq 4.8$ which occurred during time period 1963-2016 (Appendix 1) were employed to obtain moment tensor of earthquakes in each zone (Eqs. 3, 4, 2). The coordinate system considered is such that the X, Y, and Z axes are oriented in North, West, Up directions, respectively. The asymmetric strain tensor e_{ij} was calculated for each zone from Eq. 1. The symmetric (ε_{ij}) and anti-symmetric (ω_{ij}) tensors were obtained using Eqs. 6 and 7. The asymmetric strain tensors e_{ij} and symmetric strain tensors ε_{ij} for the 6 zones can be seen in Table 2. The anti-symmetric strain tensors ω_{ij} tensors for the 6 zones can be seen in Table 4.

The symmetric (ε_{ij}) tensor has 6 independent elements. Three diagonal elements of the ε_{ij} tensor represent compression (for negative elements) or extension (for positive elements) of the crust in North, West, and Up directions. The anti-symmetric (ω_{ij}) tensor has only 3 independent elements which represent clockwise rotation (for positive elements) or counterclockwise rotation (for negative elements) of the crust around Up, West, and North axes. Eigenvalues and corresponding eigenvectors of the ε_{ij} tensor

which represent the amplitude and direction of the principal strains are listed in Table 3. Rotation around Up, West, and North axes are deduced from three independent elements of the anti-symmetric (ω_{ij}) tensors (Table 4).

Table 3

Amplitude (*Am*), azimuth (*Az*), and plunge (*Pl*) of principal strains for 6 zones in the Zagros in the time interval 1963-2016

Zone				Zone			
1	ε_1			2	ε_1		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
	-9.77E-07	298	19		-7.40E-07	302	4
	ε_2				ε_2		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
	-6.38E-08	35	22		6.39E-08	34	22
	ε_3				ε_3		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
1.09E-06	170	60	5.56E-07	202	67		
3	ε_1			4	ε_1		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
	-3.61E-07	311	24		-1.46E-07	125	-5
	ε_2				ε_2		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
	1.26E-07	81	55		1.71E-08	214	10
	ε_3				ε_3		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
2.44E-07	29	-23	1.43E-07	239	-79		
5	ε_1			6	ε_1		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
	-1.58E-07	105	-12		-4.29E-07	298	17
	ε_2				ε_2		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
	-4.90E-08	27	43		2.55E-08	31	11
	ε_3				ε_3		
	<i>Am</i>	<i>Az</i>	<i>Pl</i>		<i>Am</i>	<i>Az</i>	<i>Pl</i>
4.64E-07	184	44	3.41E-07	333	-70		

Notice: Negative signs of *Am* values indicate compression while positive signs demonstrate extension in the corresponding direction.

Table 4

Anti-symmetric strain tensors and rotational nanostrain around Up, West, and North axes for 6 zones in the Zagros in the time interval 1963-2016.

Zone	ω_{ij}			Up	West	North
1	0.0E+00	-2.7E-07	6.7E-07	-273	+673	-635
	2.7E-07	0.0E+00	-6.3E-07			
	-6.7E-07	6.3E-07	0.0E+00			
2	0.0E+00	-1.1E-07	3.9E-07	-118	+398	-381
	1.1E-07	0.0E+00	-3.8E-07			
	-3.9E-07	3.8E-07	0.0E+00			
3	0.0E+00	1.8E-07	1.3E-07	+188	+132	-84
	-1.8E-07	0.0E+00	-8.4E-08			
	-1.3E-07	8.4E-08	0.0E+00			
4	0.0E+00	6.3E-08	6.2E-08	+63	+62	-90
	-6.3E-08	0.0E+00	-9.0E-08			
	-6.2E-08	9.0E-08	0.0E+00			
5	0.0E+00	-2.7E-08	3.2E-08	-27	+32	-162
	2.7E-08	0.0E+00	-1.6E-07			
	-3.2E-08	1.6E-07	0.0E+00			
6	0.0E+00	7.1E-08	2.6E-07	+71	+261	-224
	-7.1E-08	0.0E+00	-2.2E-07			
	-2.6E-07	2.2E-07	0.0E+00			

Notice: Positive signs indicate clockwise rotation while negative signs demonstrate counterclockwise rotation around the corresponding axis.

According to the sign of diagonal elements of ε_{ij} tensors (Table 2), in zones 2, 4, and 6 compression is observed in both North and West directions, while extension is observed in the Up direction. In zones 1, 3, 5, compression is observed in North direction while extension is observed in both West and Up directions. Amplitude of compression in North direction is approximately equal to amplitude of extension in West direction in zones 3 and 5 indicating a significant strain partitioning in these zones. Large compression in North direction is accompanied with small extension in West direction, indicating a small strain partitioning in zone 1.

The first principal strains (ε_1) have negative amplitudes (compression) and sub horizontal plunges in all zones (Table 3). Furthermore, the third principal strains (ε_3) have positive amplitudes (extension) and sub vertical plunges in all zones. Therefore, the first principal strains (ε_1) and the third principal strains (ε_3), respectively, indicate shortening and thickening of the

crust in all zones. Zones 1 and 2 are accompanied with large counterclockwise rotation around Up axis which indicates large rotation to East direction (Table 4). Zone 3 is accompanied with large clockwise rotation around Up axis indicating large rotation to West direction. Zone 5 is accompanied with small counterclockwise rotation around Up axis indicating small rotation to East direction. Zones 4 and 6 are accompanied with medium clockwise rotation around Up axis, indicating medium rotation to West direction.

4.2 The b value

According to Fig. 6 which has been prepared by means of the ZMAP software, completeness magnitudes (M_c) are not constant with respect to time for catalogs of the 6 zones in the Zagros region. In fact, the catalogs are composed of two or three subcatalogs with different completeness magnitudes (see vertical lines in Fig. 6). In such cases which catalog is partitioned into more than one subcatalog with different completeness magnitudes, Kijko-Sellevoll (1989) method can be employed to estimate b value.

The M_c of zone 2 suddenly drops in 2006 (Fig. 6). Therefore, catalog of zone 2 can easily be divided into two subcatalogs, one from 1963 to 2005 and another from 2006 to 2016 (see vertical line in Fig. 6). M_c of zones 1, 3, 4, 5, and 6 decreases gradually (Fig. 6). Based on the difference between maximum and minimum values of M_c , catalogs of zones 1, 3, 4, 5, and 6 were divided into three subcatalogs (Table 5). The division is such that the difference between maximum and minimum values of M_c is divided to three equal parts. For example, catalog of zone 1 was divided into three subcatalogs, first one from 1963 to 1993 ($M_c \sim 4.68$ to 4.04), second from 1994 to 2006 ($M_c \sim 4.04$ to 3.41), and third one from 2007 to 2016 ($M_c \sim 3.41$ to 2.78).

M_c of subcatalogs containing less than 600 events was obtained using maximum curvature method (Mignan and Woessner 2012, Wiemer and Wyss 2000). M_c of subcatalogs containing more than 600 events was obtained using entire-magnitude-range method (Mignan and Woessner 2012, Woessner and Wiemer 2005). After removing events smaller than M_c from all subcatalogs, b values were estimated using Kijko-Sellevoll (1989) method discussed in Section 3.2. The resulting b values and corresponding errors are listed in Table 5.

Spatial distribution of b value is very heterogeneous in the Zagros (Table 5), which may be due to heterogeneity in material properties of the source region (Mogi 1962) and stress distribution (Scholz 1968). The b value varies from 0.64 to 0.92 in the Zagros (Table 5) which is in agreement with Frohlich and Davis (1993). Lower b values are estimated in areas in which larger earthquakes are abundant (Gutenberg and Richter 1944). Lower b val-

ues are expected in homogeneous and resistant regions (Mogi 1962, Tsapanos 1990). Thrust zones have b value smaller than 1, strike-slip zones have b value around 1 (Schorlemmer *et al.* 2005). According to Fig. 2 and several authors (*e.g.*, Baker *et al.* 1993, Mostafazadeh *et al.* 2000, Talebian and Jackson 2004), thrust and strike-slip faulting are dominant in the Zagros. The b values in the Zagros (0.64 to 0.92) are around and smaller than 1, which is in agreement with Schorlemmer *et al.* (2005). In detail, zones 1, 2, 4, and 5, in which thrust faulting is dominant (Fig. 2), have small b values (0.69, 0.69, 0.72, and 0.64). On the other hand, zones 3 and 6, in which number of earthquakes with strike-slip focal mechanism is significant (Fig. 2), have b values near to 1 (0.92 and 0.87).

Table 5

The b value of 6 zones in the Zagros
for the time interval 1963-2016

Zone	Max. M_c	Time span of subcatalogs	b value	Error of b value
1	4.7	1963-1993 1994-2006 2007-2016	0.69	0.01
2	4.4	1963-2005 2006-2016	0.69	0.02
3	4.4	1963-2002 2003-2005 2006-2016	0.92	0.03
4	4.6	1963-2002 2003-2005 2006-2016	0.72	0.02
5	4.2	1963-2004 2005-2006 2007-2016	0.64	0.01
6	4.5	1963-2003 2004-2006 2007-2016	0.87	0.01

Notice: Max. M_c stands for maximum value of completeness magnitude during 1963-2016 (see Fig. 6). Catalog of each zone is divided into two or three subcatalogs to estimate the corresponding b value (see Fig. 6).

Fig. 6. Continued on next page.

Fig. 6. Variations and maximum value of completeness magnitude (M_c) during 1963-2016 in catalog of zones 1 to 6 in the Zagros. The completeness magnitudes are estimated using maximum curvature method (Wiemer and Wyss 2000) and moving window approach with a window of 200 events, moved by 150 events. Dashed lines indicate one standard deviation from the average. The uncertainties in the completeness magnitudes (dashed lines) are obtained from $N = 200$ bootstrap samples. Original catalog of each zone is divided into two or three subcatalogs to estimate the corresponding b value (see Table 5). Vertical lines indicate time span of the corresponding subcatalogs (see Table 5).

4.3 Recurrence interval of large earthquakes ($M > 6$)

The strain rate tensor ($\dot{\epsilon}_{ij}$) during time interval T can be obtained through dividing strain tensor (ϵ_{ij}) by the time interval T . Our dataset contains earthquakes which occurred in the time period from 1963 to 2016. Therefore, the strain rate tensors ($\dot{\epsilon}_{ij}$) were obtained by dividing strain tensor (ϵ_{ij}) in each zone (Table 2) by $T = 53$ years (Table 6). The largest absolute eigenvalue of seismic strain rate tensor is considered as $\dot{\epsilon}_{\max}$ (Table 6). Thereafter, seismic moment rates ($\dot{M}_{\text{seismic}}$) were obtained from Eq. 12 (Table 7). Thickness of seismogenic layer in the Zagros is considered to be 15 km (*e.g.*, Ekstrom and England 1989, Jackson and McKenzie 1988).

Table 6

The strain rate tensor $\dot{\epsilon}_{ij}$ and corresponding eigenvalues (λ) of 6 zones in the Zagros in the time interval 1963-2016

Zone				λ	$\dot{\epsilon}_{\max}$
1	-1.3E-08	5.3E-09	6.3E-09	-1.84E-08	2.06E-08
	5.3E-09	7.2E-10	-1.1E-08	-1.20E-09	
	6.3E-09	-1.1E-08	1.3E-08	2.06E-08	
2	-9.4E-09	7.3E-09	-3.4E-10	-1.39E-08	1.39E-08
	7.3E-09	-1.8E-09	-3.6E-09	1.20E-09	
	-3.4E-10	-3.6E-09	9.0E-09	1.05E-08	
3	-1.5E-09	4.5E-09	2.2E-09	-6.82E-09	6.82E-09
	4.5E-09	5.3E-10	-2.9E-09	2.39E-09	
	2.2E-09	-2.9E-09	1.1E-09	4.61E-09	
4	-1.6E-09	1.4E-09	6.0E-10	-2.77E-09	2.77E-09
	1.4E-09	-6.5E-10	9.6E-11	3.23E-10	
	6.0E-10	9.6E-11	2.6E-09	2.71E-09	
5	-2.7E-09	7.8E-10	1.1E-10	-2.99E-09	8.76E-09
	7.8E-10	3.8E-09	-4.9E-09	-9.25E-10	
	1.1E-10	-4.9E-09	3.7E-09	8.76E-09	
6	-5.4E-09	2.9E-09	3.0E-09	-8.09E-09	8.09E-09
	2.9E-09	-6.6E-10	-2.8E-09	4.82E-10	
	3.0E-09	-2.8E-09	4.9E-09	6.44E-09	

Notice: $\dot{\epsilon}_{\max}$ is the largest absolute eigenvalue.

Table 7

Area (A), thickness of the seismogenic layer (H_s) and seismic moment rate ($\dot{M}_{\text{seismic}}$) of 6 zones in the Zagros for the time period 1963-2016

Zone	$\dot{\epsilon}_{\text{max}}$	A [km ²]	H_s [km]	$\dot{M}_{\text{seismic}}$ [Nm/yr]
1	2.06E-08	53647	15	9.96E+17
2	1.39E-08	32768	15	4.12E+17
3	6.82E-09	11064	15	6.80E+16
4	2.77E-09	11783	15	2.94E+16
5	8.76E-09	17515	15	1.38E+17
6	8.09E-09	31534	15	2.29E+17

Notice: $\dot{\epsilon}_{\text{max}}$ is the largest absolute eigenvalue of the strain rate tensors $\dot{\epsilon}_{ij}$ (see Table 6).

Table 8

Seismic moment rate ($\dot{M}_{\text{seismic}}$), maximum earthquake magnitude from frequency-magnitude plot (M_{max} (theoretical)), maximum earthquake magnitude from catalog (M_{max} (observed)), maximum possible earthquake magnitude (M_{max}), b value, and recurrence interval (T) for earthquake larger than $M_w = 6$ for 6 zones in the Zagros

Zone	$\dot{M}_{\text{seismic}}$ [Nm/yr]	M_{max} (theoretical)	M_{max} (observed)	M_{max}	b value	T [year]
1	9.96E+17	6.7	6.9	6.9	0.69	10
2	4.12E+17	6.6	6.7	6.7	0.69	14
3	6.80E+16	6.1	5.9	6.1	0.92	46
4	2.94E+16	6.1	5.8	6.1	0.72	114
5	1.38E+17	6.1	6.1	6.1	0.64	25
6	2.29E+17	6.4	6.2	6.4	0.87	13

Theoretical maximum earthquake magnitude (M_{max} (theoretical)) is estimated from frequency-magnitude plot for each zone (Fig. 7 and Table 8). In fact, M_{max} (theoretical) can be obtained from extrapolating the straight line fitted to the frequency-magnitude plot (Gutenberg and Richter 1954). As Mignan and Woessner (2012) asserted, for a catalog in which Mc is not constant during time span of the catalog, maximum value of Mc must be considered as Mc of the whole catalog. Accordingly, we removed events smaller than maximum values of Mc for the 6 zones (Table 5 and Fig. 6) to estimate M_{max} (theoretical) in the 6 zones (Fig. 7). Observed maximum earthquake magnitudes (M_{max} (observed)) in seismic catalog are also reported in Table 8.

Fig. 7. Frequency-magnitude plots of 6 zones in the Zagros for the time period 1963-2016. Theoretical maximum earthquake magnitude $M_{\max}$ (theoretical) can be obtained from the intercept of the best fitted line to magnitude axis.

Maximum possible earthquake magnitude $M_{\max}$ is considered as maximum value of $M_{\max}$ (theoretical) and $M_{\max}$ (observed). Recurrence intervals of earthquakes with $M > 6$ for the zones are calculated using Eq. 11 (Table 8).

Figure 5 shows that five large earthquakes ($M > 6$) occurred during 1963-2016 in zone 1. Resulted recurrence interval of large earthquakes ($M > 6$) for zone 1 is $T = 10$ years (Table 8). Five large earthquakes occurred in zone 2 and $T = 14$ years. No large earthquake occurred in zone 3 and $T = 46$ years. No large earthquake occurred in zone 4 and $T = 114$ years. Two large earthquakes occurred in zone 5 and $T = 25$ years. Four large earthquakes occurred in zone 6 and $T = 13$ years. Estimated recurrence intervals of large

earthquakes in zones 1, 2, 5, 6 are in agreement with recurrence intervals expected from seismicity behavior during 1963-2016 (Fig. 5). Estimated recurrence intervals of large earthquakes in zones 3 and 4 (46 and 114 years) are approximately equal and longer than the time span of the catalog (53 years). Absence of large earthquakes ($M > 6$) during 1963-2016 in zones 3 and 4 (Fig. 5) confirms the resulting long recurrence intervals of large earthquakes (46 and 114 years).

4.4 Correlation between b value, seismic moment rate, and recurrence interval

Recurrence interval of large earthquakes ($M > 6$) is dependent on both b value and seismic moment rate (Eq. 11). It is clear from Eq. 11 that recur-

Fig. 8: (A) Variations of recurrence interval of large earthquakes ($M > 6$) and seismic moment rate along 6 zones of the Zagros; (B) Correlation between variations of the recurrence interval of large earthquakes and seismic moment rate.

Fig. 9: (A) Variations of recurrence interval of large earthquakes ($M > 6$) and b value along 6 zones of the Zagros; (B) Correlation between variations of recurrence interval of large earthquakes and b value.

recurrence interval is explicitly proportional to reverse seismic moment rate. However, recurrence interval dependence on b value is implicit. In fact, it is not clear whether the recurrence interval is proportional to b value or reverse b value. Furthermore, individual portions of seismic moment rate and b value variations in recurrence interval variations are not known. To overcome these challenges, variations of recurrence interval of large earthquakes and seismic moment rate along 6 zones of the Zagros are shown in Fig. 8A.

Correlation between variations of the recurrence interval and seismic moment rate is $r = -0.57$ (Fig. 8B). The quite strong and negative correla-

tion indicates that small recurrence intervals of large earthquakes are related to large seismic moment rates and *vice versa* in the Zagros. In other words, the recurrence interval increases as seismic moment rate decreases. Thus, recurrence interval is proportional to reverse seismic moment rate. Furthermore, recurrence interval variations have 57 percent correlation with seismic moment rate variations.

Variations of recurrence interval and b value along 6 zones of the Zagros can be seen in Fig. 9A. Correlation between variations of the recurrence interval and b value is $r = +0.03$ (Fig. 9B). Therefore, recurrence interval is proportional to b value. The absolutely weak and positive correlation indicates that recurrence interval variations have only 3 percent correlation with b value variations.

5. CONCLUSIONS

To elucidate the details, we divided the Zagros region to 6 zones and calculated seismic strain tensors in each zone in the time interval from 1963 to 2016. The symmetric and anti-symmetric strain tensors are also calculated to investigate dilatation, shear and rotational strains individually. The predominant state of deformation in the 6 zones is the shortening and thickening of the crust, which is characteristic of tectonic regions where orogeny is processing. Our results indicate the Zagros is underthrusting beneath the Central Iran at a sub horizontal angle. Seismic strain tensors indicate significant strain partitioning in the North Zagros which results in Westward rotation of middle and north parts of the Zagros.

On average, the Central Zagros has higher seismic strain than the North Zagros. In the North and Central Zagros, the main principal strain axes have sub horizontal plunges with Northwest-Southeast and Northeast-Southwest directions. Thus, deformation state of the North and Central Zagros is composed of both shortening upright to strike of the Zagros and strike slip motions parallel to strike of the Zagros.

The b value was also investigated in the Zagros region in the time interval 1963-2016. The b values in the Central Zagros are lower than the North Zagros. Seismic moment rates in the Central Zagros are higher than in the North Zagros. The recurrence intervals of large earthquakes ($M > 6$) in the Central Zagros are shorter than in the North Zagros. We conclude stating that the recurrence intervals are in agreement with the resulting b values and seismic moment rates. A quite strong and negative correlation is observed between variations of recurrence interval and seismic moment rate, while there is an absolutely weak and positive correlation between variations of recurrence interval and b value in the Zagros. Therefore, recurrence interval

variations are more dependent on seismic moment rate variations than b value variations in the Zagros.

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Appendix

The Zagros earthquakes with $M_w \geq 4.8$ occurred 1963-2016. Coordinates of the 6 zones are listed in Table 1 and Fig. 5. Columns are: date, latitude, longitude, strike, dip, rake (fault plane), strike, dip, rake (auxiliary plane), depth [km], scalar moment, M_w , reference (H = Harvard GCMT Solutions; EE = Ekstrom and England 1989; B = Baker 1993; BJP = Baker *et al.* 1993; MJPB = Maggi *et al.* 2000; TJ = Talebian and Jackson 2004; AM = Ashkpour and Mostafazadeh 2008). HK in M_0 column indicates that scalar moment is obtained from the corresponding M_w using the relation $M_w = 2/3 \log M_0 - 10.7$ (Hanks and Kanamori 1979). Single stars indicate that latitude and longitude are reported from ISC catalog. Double stars indicate that latitude and longitude are reported from the International Institute of Earthquake Engineering and Seismology, Tehran, Iran, catalog (www.iiees.ac.ir).

Zone 1												
Date	Lat. (°N)	Long. (°E)	s_1	d_1	r_1	s_2	d_2	r_2	Depth [km]	M_0 (10^{18})	M_w	Ref.
1965/6/21	28.10	55.84	313	60	110	97	36	59	8	1.122 (HK)	6.0	TJ
1966/9/18	27.82	54.27	269	34	96	82	56	86	12	0.794 (HK)	5.9	TJ
1970/2/23	27.82	54.47	286	44	90	106	46	90	9	0.281 (HK)	5.6	TJ
1970/2/28	27.83	56.31	264	40	90	84	50	90	-	0.199 (HK)	5.5	TJ
1971/4/12	28.26	55.61	261	35	90	81	55	90	10	0.794 (HK)	5.9	TJ
1971/11/8	27.01	54.46	300	42	90	120	48	90	9	0.794 (HK)	5.9	TJ

1971/12/9	27.29	56.37	276	40	55	138	58	116	-	0.562 (HK)	5.8	TJ
1974/12/2	28.09	55.86	268	27	110	65	65	80	7	0.09	5.2	B
1975/3/7	27.48	56.23	90	60	90	270	30	90	11	1.584 (HK)	6.1	TJ
1975/12/24	27.02	55.48	260	34	90	80	56	90	8	0.199 (HK)	5.5	TJ
1976/3/16	27.31	54.98	253	40	90	73	50	90	9	0.070 (HK)	5.2	TJ
1977/ 1/ 5	27.46	56.20	204	43	40				29	0.052	5.1 (H)	EE
1977/ 3/21	27.61	56.39	267	27	98				18.8	14	6.7 (H)	EE
1977/ 3/21	27.60	56.52	241	26	77				19.3	1.81	6.1 (H)	EE
1977/ 3/22	27.60	56.42	77	34	112				12	1.5	6.0	MJ PB
1977/ 3/23	27.62	56.59	260	41	92				10	0.228	5.5 (H)	EE
1977/3/24	27.66	56.60	302	30	90	122	60	90	-	0.10 (HK)	5.3	TJ
1977/ 4/ 1	27.55	56.33	262	44	90				10	0.956	5.9 (H)	EE
1977/10/19	27.79	54.88	117	41	120				15	0.216	5.5 (H)	EE
1977/12/10	27.68	56.60	291	28	138				18	0.29	5.6	MJ PB
1980/11/17	27.36	56.08	251	30	87				15	0.0867	5.2 (H)	EE
1980/11/28	27.59	56.50	311	37	134				15	0.136	5.4 (H)	EE
1981/ 4/16	27.73	56.35	221	42	8				15	0.0524	5.1 (H)	EE
1983/ 2/18	27.95	53.85	272	20	94				15	0.0688	5.2 (H)	EE
1983/ 7/12	27.61	56.40	227	50	75				17	1.00	5.9	MJ PB
1984/12/22	27.83	54.44	116	41	84				49	0.054	5.1 (H)	EE
1987/ 4/29	27.42	56.11	265	41	112				10	0.37	5.6	MJ PB
1987/ 5/12	28.16	55.53	278	34	104				15	0.175	5.4 (H)	EE
1987/12/18	28.15	56.66	160	44	-145	43	67	-52	10	0.672 (H)	5.8	B
1988/ 6/ 9	27.67	56.10	310	11	139	81	83	82	15	0.0806	5.2	H
1990/11/ 6	28.32	55.46	275	30	101				7	7.1	6.5	MJ PB

1991/ 5/22	27.38	55.77	288	18	80	118	72	93	13	0.12 (H)	5.4	TJ
1992/ 5/19	28.05	55.35	254	40	99	63	51	83	15	0.294	5.6	H
1993/ 7/ 9	28.39	55.33	277	69	83	115	22	107	16	0.0742 (H)	5.1	TJ
1995/ 1/24	27.64	55.65	217	31	56	75	64	109	15	0.0312	4.9	H
1996/5/24	27.85	53.57	109	43	81	301	47	98	6	0.0775 (H)	5.0	TJ
1997/ 7/27	27.41	56.56	108	76	175	199	85	15	33	0.0582	5.1	H
1997/10/ 3	27.79	54.73	281	9	102	89	81	88	4	0.101 (H)	5.3	TJ
1998/ 8/ 1	27.74	56.51	280	52	93	95	38	86	9	0.0637 (H)	5.1	TJ
1998/11/13	27.76	53.62	318	32	120	104	63	73	7	0.16 (H)	5.4	TJ
1999/ 4/30	27.81 *	53.56 *	321	53	134	82	55	47	44.9	0.0597	5.1	H
2000/ 3/ 5	27.95	56.47	313	44	101	117	47	80	12	0.163 (H)	5.4	TJ
2001/ 4/13	28.20 *	54.86 *	295	67	64	166	34	135	26.1	0.0551	5.1	H
2002/ 4/17	27.30	56.66	117	68	123	237	39	36	33	0.0911	5.2	H
2003/ 2/14	27.48	56.77	288	18	97	100	73	88	25	0.292	5.6	H
2003/ 7/10	28.35	54.10	277	33	93	93	57	88	15	0.479	5.7	H
2003/ 7/10	28.26	54.05	310	65	114	83	34	49	15	0.359	5.6	H
2003/10/24	28.25 *	54.03 *	128	39	70	333	54	105	33	0.0401	5.0	H
2003/11/ 5	27.09	56.15	231	52	78	70	39	105	33	0.0266	4.9	H
2003/11/28	28.26 *	54.02 *	255	74	100	43	19	60	33	0.0378	5.0	H
2003/12/15	28.25 *	54.12 *	272	43	90	92	47	90	15	0.0485	5.1	H
2005/11/27	27.00 **	55.79 **	308	88	-177	218	87	-2	12	0.213	5.5	H
2005/12/27	28.01	56.18	257	32	76	94	59	99	18.3	0.0196	4.8	H
2006/ 3/25	27.57	55.76	308	30	95	113	60	100	17	0.672	5.9 (H)	AM
2006/ 3/25	27.48	55.68	276	35	89	98	55	91	12	0.214	5.5	H
2006/ 3/25	27.41	55.66	267	30	70	110	62	101	12	0.081	5.2	H
2006/ 3/25	27.53	55.62	261	33	59	116	62	108	12	0.0357	5.0	H
2006/ 3/25	27.44	55.36	256	34	57	114	62	110	19.3	0.0269	4.9	H
2006/ 6/ 3	26.91 **	55.91 **	260	49	69	111	45	112	12	0.0651	5.1	H
2006/ 9/10	27.54	54.29	321	52	147	73	65	43	23.1	0.0367	5.0	H
2007/ 2/27	27.97	55.23	280	42	108	76	50	74	22.8	0.0344	5.0	H
2007/ 3/23	27.48	55.12	265	42	69	113	51	108	12	0.0347	5.0	H
2007/ 4/25	28.04	56.34	282	34	94	98	56	87	18.6	0.0892	5.2	H

2007/ 7/24	27.14	55.65	270	21	81	100	69	94	20.5	0.0336	5.0	H
2007/ 8/25	28.05	56.74	314	85	-178	224	88	-5	23.5	0.0444	5.0	H
2008/ 5/ 5	28.36 *	54.08 *	290	36	88	113	54	92	12.4	0.07	5.2	H
2008/ 9/10	26.93 **	55.73 **	234	33	76	71	58	99	12	1.74	6.1	H
2008/ 9/17	27.20 **	55.94 **	245	45	59	106	53	117	12	0.0944	5.2	H
2009/11/ 3	27.04	56.16	246	30	63	96	64	105	13.2	0.0387	5.0	H
2010/ 4/27	27.09	54.80	156	76	-175	64	86	-15	20	0.0374	5.0	H
2010/ 7/20	27.03 *	53.89 *	269	33	59	124	62	109	12	0.574	5.8	H
2011/10/19	27.92	54.31	282	51	87	107	39	94	15.5	0.0722	5.2	H
2012/ 5/13	27.06 *	53.95 *	306	34	112	100	58	76	12	0.0619	5.1	H
2012/ 9/ 6	27.11 *	53.99 *	146	73	175	237	85	17	12	0.0862	5.2	H
2013/ 7/ 2	27.10	54.92	286	49	79	122	42	102	22.8	0.0291	4.9	H
2014/1/2	26.95	54.36	329	54	141	85	59	43	12	0.113	5.3	H
2014/11/10	27.75	55.71	349	41	180	79	90	49	15	0.0838	5.2	H
2014/11/15	28.04	55.13	247	41	66	97	53	109	22.2	0.0203	4.8	H
2015/ 1/25	27.27	56.14	299	36	112	92	57	75	12.6	0.0292	4.9	H
2015/ 3/ 5	27.82	56.66	260	27	91	79	63	90	31.1	0.0289	4.9	H
Zone 2												
Date	Lat. (°N)	Long. (°E)	s_1	d_1	r_1	s_2	d_2	r_2	Depth [km]	M_0 (10^{18})	M_w	Ref.
1968/9/14	28.43	53.18	288	30	90	108	60	90	7	0.562 (HK)	5.8	TJ
1972/4/10	28.43	52.82	288	49	99				9	8.44	6.6	BJP
1972/4/10	28.43	52.82	322	40	98				10	3.69	6.7	BJP
1976/ 4/22	28.71	52.12	312	52	80				7	0.38	5.7	BJP
1981/ 4/ 1	28.85	51.50	351	34	144				15	0.0777	5.2 (H)	EE
1985/ 2/ 2	28.36	52.97	128	37	91				11	0.28	5.6	MJ PB
1985/ 8/ 7	27.88	53.05	303	39	116				15	0.257	5.5 (H)	EE
1986/ 5/ 2	27.97	53.24	107	47	57				15	0.239	5.5 (H)	EE
1986/ 5/ 3	27.98	53.31	110	33	60				15	0.0755	5.2 (H)	EE
1990/12/16	29.05	51.31	144	67	87				15	0.411	5.7	BJP
1993/ 1/ 6	29.31	52.02	339	90	-166	248	76	0	15	0.149	5.4	H
1993/ 3/29	28.00 **	52.74 **	305	64	99	104	28	72	40	0.0733	5.2	H
1994/ 3/ 1	29.14	52.63	239	87	15	149	75	177	13	1.37 (H)	5.9	TJ

1994/ 3/29	29.20	51.36	334	40	104	136	52	79	7	0.0535 (H)	5.1	TJ
1994/ 3/30	28.96	52.60	148	71	177	239	87	19	33	0.158	5.4	H
1994/ 4/ 3	29.01	52.72	142	79	-159	47	69	-11	33	0.0807	5.2	H
1994/ 6/20	29.05	52.67	255	74	-3				9	0.60	5.8	MJ PB
1999/ 5/ 6	29.50	51.88	142	78	-167	49	77	-12	7	1.90 (MJPB)	6.1	TJ
1999/10/31	29.36	51.48	324	58	105	117	34	67	33	0.0688	5.2	H
2000/ 3/ 1	28.40	52.85	267	69	106	49	26	55	15	0.0403	5.0	H
2004/ 3/ 2	28.90 **	51.17 **	33	90	-161	303	71	0	16.1	0.0548	5.1	H
2005/ 8/ 9	28.90	52.52	139	75	117	257	30	31	16.1	0.055	5.1	H
2010/11/26	27.94	52.47	281	42	70	128	51	107	12	0.204	5.5	H
2012/10/10	29.11	52.56	316	52	120	93	47	57	14.9	0.0258	4.9	H
2014/4/16	28.48	51.50	193	79	-176	102	86	-11	19.1	0.0254	4.9	H
2014/10/28	28.32	52.91	325	53	135	86	56	47	18.9	0.0395	5.0	H
2014/12/30	28.54	51.88	230	36	-173	134	86	-54	17	0.0477	5.1	H
2015/1/10	28.64	51.85	219	65	177	311	87	25	21.8	0.0202	4.8	H
Zone 3												
Date	Lat. (°N)	Long. (°E)	s_1	d_1	r_1	s_2	d_2	r_2	Depth [km]	M_0 (10^{18})	M_w	Ref.
1968/6/23	29.81	51.16	136	45	88				9	0.22	5.5	BJP
1971/4/6	29.80	51.88	62	79	2				6	0.072	5.3	BJP
1981/4/1	29.84	51.50	351	34	144				15	0.078	5.4	BJP
1986/ 7/12	29.96	51.58	4	73	-159				4	0.26	5.5	BJP
1986/12/20	29.98	51.62	344	65	163				8	0.11	5.3	BJP
1988/ 8/11	29.97	51.57	3	69	-175				7	0.24	5.5	BJP
1988/ 8/11	29.97	51.67	350	82	-166				9	0.65	5.8	BJP
1988/ 8/30	29.95	51.70	337	83	-147				15	0.061	5.1	BJP
1988/12/ 6	29.94	51.65	357	74	198				10	0.32	5.6	BJP
1989/ 5/ 3	29.96	51.65	153	55	-166				15	0.084	5.1	BJP
1992/ 9/11	29.96	51.11	302	33	67	148	60	104	15	0.121	5.3	H
1996/11/18	29.76	51.12	177	62	-177	85	87	-28	33	0.085	5.2	H
2000/5/3	29.66	50.80	292	26	53	152	69	6	5	0.0448 (H)	5.1	TJ
2000/ 6/23	29.93	51.25	180	75	175	272	85	15	33	0.0612	5.1	H
2002/ 6/ 1	29.57	51.23	170	88	148	261	58	2	33	0.0378	5.0	H
2003/ 5/27	29.45	51.50	290	79	45	189	46	165	33	0.0973	5.3	H
2010/ 9/27	29.56	51.62	309	6	100	119	85	89	17.1	0.938	5.9	H
2010/ 12/1	30.02	51.46	355	68	-172	262	82	-22	23.4	0.0272	4.9	H
2011/ 1/ 5	30.08	51.56	5	84	-174	274	84	-6	21.3	0.144	5.4	H
2011/ 1/ 7	30.03	51.64	343	84	-164	252	74	-6	23.6	0.043	5.0	H
2011/ 1/ 8	30.10	51.62	7	80	-168	275	78	-11	20.5	0.0628	5.1	H
2011/ 3/ 5	29.99	51.05	302	49	87	126	41	93	12	0.102	5.3	H
2012/ 6/ 8	29.69	50.62	315	36	87	139	54	92	13.3	0.0369	5.0	H

2014/5/21	29.51	50.88	315	38	118	101	57	70	18.6	0.0405	5.0	H
Zone 4												
Date	Lat. (°N)	Long. (°E)	s_1	d_1	r_1	s_2	d_2	r_2	Depth [km]	M_0 (10^{18})	M_w	Ref.
1972/7/2	30.06	50.85	132	64	90	312	26	90	9	0.1 (HK)	5.3	TJ
1979/3/28	30.90	49.93	317	42	92				15	0.0745	5.2 (H)	EE
1989/ 5/27	29.86	50.69	332	57	122	103	45	51	15	1.25	6.0	H
1991/11/4	30.69	50.25	135	80	78	6	16	140	5	0.311 (H)	5.8	TJ
1993/ 3/26	30.54	50.65	152	88	-164	61	74	-3	33	0.0518	5.1	H
1993/6/22	30.18	50.83	301	44	65				5	0.0901	5.2	MJ PB
1993/10/21	30.36	50.95	271	50	80	105	41	101	15	0.0359	5.0	H
1995/ 4/22	30.87	49.46	121	61	92	297	29	86	14	0.0975 (H)	5.1	TJ
2001/ 3/28	30.20	50.43	327	80	97	113	12	56	15	0.113	5.3	H
Zone 5												
Date	Lat. (°N)	Long. (°E)	s_1	d_1	r_1	s_2	d_2	r_2	Depth [km]	M_0 (10^{18})	M_w	Ref.
1977/ 4/ 6	31.96	50.67	228	48	36	112	64	132	6	1.3 (EE)	5.9	B
1978/12/14	32.14	49.65	150	34	100				15	1.95	6.1 (H)	EE
1983/ 3/5	32.19	49.08	254	4	32	133	88	93	10.1	0.351	5.6	H
1985/ 3/27	31.66	49.94	71	31	-116				83.8	0.0593	5.1 (H)	EE
1985/ 9/18	31.59	49.44	143	36	74				11	0.110	5.3 (H)	EE
1992/ 3/ 4	31.64	50.71	122	79	173	213	83	12	33	0.0572	5.1	H
1998/ 6/15	31.71	50.77	294	26	123	78	68	75	5	0.0797 (H)	5.0	TJ
2002/ 9/25	32.04	49.10	303	46	78	141	45	103	15	0.302	5.6	H
2005/10/20	31.77	50.47	131	83	152	224	62	8	29.1	0.0444	5.0	H
2006/ 9/26	32.01	50.72	147	79	168	239	78	11	24.8	0.026	4.9	H
2012/ 7/ 1	31.67	50.90	254	58	73	103	35	115	16.8	0.0519	5.1	H
2012/ 7/24	31.72	50.92	253	57	72	104	37	115	17.8	0.0346	5.0	H
2013/ 1/12	31.75	50.95	247	61	40	135	56	144	21.2	0.033	4.9	H
2013/ 1/25	31.71	51.03	295	44	110	87	50	71	20.9	0.0385	5.0	H
Zone 6												
Date	Lat. (°N)	Long. (°E)	s_1	d_1	r_1	s_2	d_2	r_2	Depth [km]	M_0 (10^{18})	M_w	Ref.
1966/7/27	32.67	48.78	294	34	119	80	61	72	-	0.1 (HK)	5.3	TJ
1976/11/7	33.21	47.90	138	58	121	269	43	50	-	0.0177 (HK)	4.8	TJ

1977/4/26	32.66	48.92	293	29	93				19.6	0.197	5.5 (H)	EE
1977/6/5	32.64	48.09	293	34	91				10	1.55	6.1 (H)	EE
1977/6/5	32.56	48.16	289	33	91				10	0.130	5.3 (H)	EE
1980/10/19	32.70	48.58	327	19	120				17	0.32	5.6	MJ PB
1981/1/2	32.73	48.46	277	24	95				15	0.0981	5.3 (H)	EE
1983/ 5/28	32.58	48.55	314	38	113				27.3	0.253	5.5 (H)	EE
1987/ 5/29	33.54	47.76	128	88	170	218	80	2	15	0.10	5.3	H
1989/ 4/ 2	32.89	47.62	351	85	-130	256	40	-7	15	0.142	5.4	H
1990/ 8/ 3	32.80	48.24	318	64	111	96	33	53	15	0.11	5.3	H
1990/10/11	32.41	47.89	308	45	90	128	45	90	15	0.0355	5.0	H
1994/ 7/31	32.69	48.42	288	17	90				14	0.2	5.5	MJ PB
1998/10/ 4	33.32	47.26	288	53	88	111	37	92	9	0.115 (H)	5.2	TJ
1998/10/ 5	33.26	47.26	290	51	84	119	39	97	7	0.137 (H)	5.3	TJ
2001/ 4/ 3	32.58	47.80	270	62	77	116	31	113	30.7	0.0746	5.2	H
2001/ 9/ 1	32.81	47.58	288	60	83	121	31	101	15	0.0413	5.0	H
2004/11/21	33.23	47.75	310	26	112	106	66	80	12	0.0681	5.2	H
2004/11/22	33.21	47.82	308	29	111	105	63	79	12.1	0.0371	5.0	H
2004/11/27	33.18	47.80	330	38	145	89	69	57	20.3	0.0244	4.9	H
2005/ 5/ 3	33.73	48.64	316	74	-161	220	71	-17	21.6	0.0316	4.9	H
2006/ 3/30	33.65	48.78	321	70	-167	226	77	-20	19.5	0.0621	5.1	H
2006/ 3/31	33.74	48.73	313	78	-174	222	84	-12	17	1.71	6.1	H
2006/ 3/31	33.73	48.75	319	67	-168	224	79	-24	25.7	0.0538	5.1	H
2008/ 9/ 3	32.44	47.10	294	34	78	128	57	98	12	0.057	5.1	H
2010/ 2/23	32.52	48.18	286	33	72	127	59	101	16.6	0.0288	4.9	H
2010/ 2/23	32.60	48.21	307	55	111	93	40	62	15.5	0.0697	5.2	H
2012/ 4/18	32.52	46.93	328	47	129	98	55	56	12	0.0275	4.9	H
2012/ 4/20	32.50	46.90	292	34	78	127	57	98	12	0.0436	5.0	H
2012/ 5/ 3	32.66	47.60	303	40	101	109	51	81	21.1	0.161	5.4	H
2013/ 1/22	33.07	48.60	323	44	134	90	60	56	21.2	0.0219	4.8	H
2014/8/17	32.62	47.34	311	30	107	111	62	80	20.2	0.0178	4.8	H
2014/8/18	32.59	47.53	317	27	111	114	65	80	12	2.57	6.2	H
2014/8/18	32.59	47.60	331	38	137	98	65	60	18	0.595	5.8	H
2014/8/18	32.56	47.45	274	32	78	109	59	97	12	0.0737	5.2	H
2014/8/18	32.68	47.38	336	59	171	70	83	31	16.5	0.183	5.4	H
2014/8/18	32.50	47.57	300	30	108	99	62	80	12	1.06	6.0	H
2014/8/19	32.63	47.32	289	29	84	116	61	93	12	0.0954	5.3	H
2014/8/20	32.51	47.62	310	22	109	109	69	82	13.9	0.32	5.6	H

2014/8/22	32.68	47.54	293	44	98	101	46	82	28.7	0.0262	4.9	H
2014/8/23	32.57	47.64	347	52	149	98	66	43	18.9	0.14	5.4	H
2014/8/24	32.61	47.76	58	66	0	328	90	156	24.7	0.0493	5.1	H
2014/10/15	32.45	47.87	89	37	88	272	53	92	12	0.628	5.8	H

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