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ORIGINAL ARTICLE

# Updated earthquake catalogue for seismic hazard analysis in Pakistan

**Sarfraz Khan** · **Muhammad Waseem** · **Muhammad Asif Khan** · **Waqas Ahmed**

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**Abstract** A reliable and homogenized earthquake catalogue is essential for seismic hazard assessment in any area. This article describes the compilation and processing of an updated earthquake catalogue for Pakistan. The earthquake catalogue compiled in this study for the region (quadrangle bounded by the geographical limits 40–83° N and 20–40° E) includes 36,563 earthquake events, which are reported as 4.0–8.3 moment magnitude ($M_W$) and span from 25 AD to 2016. Relationships are developed between the moment magnitude and body, and surface wave magnitude scales to unify the catalogue in terms of magnitude $M_W$. The catalogue includes earthquakes from Pakistan and neighbouring countries to minimize the effects of geopolitical boundaries in seismic hazard assessment studies. Earthquakes reported by local and international agencies as well as individual catalogues are included. The proposed catalogue is further used to obtain magnitude of completeness after removal of dependent events by using four different algorithms. Finally, seismicity parameters of the seismic sources are reported, and recommendations are made for seismic hazard assessment studies in Pakistan.

**Keywords** Earthquake catalogue · Pakistan · Completeness analysis · Moment magnitude · *b* value · Z-Map

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s10950-018-9736-y) contains supplementary material, which is available to authorized users.

S. Khan (✉) · M. Waseem · W. Ahmed
National Centre of Excellence in Geology, University of Peshawar, Peshawar, Pakistan
e-mail: sarfraz_qau@yahoo.com

M. A. Khan
University of Peshawar, Peshawar, Pakistan

## 1 Introduction

A reliable and homogenized earthquake catalogue is an important prerequisite for a probabilistic seismic hazard analysis (PSHA). Ideally, an earthquake catalogue should report all events that contribute to a seismic hazard. A single source is not enough to report all earthquakes, and therefore, catalogues are composites, i.e. having contributions from all available sources. Earthquakes occur frequently in and around Pakistan, and thus, a complete catalogue is essential for seismic hazard estimation. The objective of this research is to compile an updated, composite earthquake catalogue of Pakistan from the perspective of seismic hazard analysis. Moreover, processing of this earthquake catalogue, as well as the final outcomes, is presented as an input parameter to a PSHA.

Previous attempts have been made to compile an earthquake catalogue of Pakistan, which was included during the development of seismic provisions for the Building Code of Pakistan (BCP 2007) and, more recently, by Zare et al. (2014) and Waseem et al. (2018). Therefore, a fresh attempt is attempted to compile the catalogue in this study. The catalogue

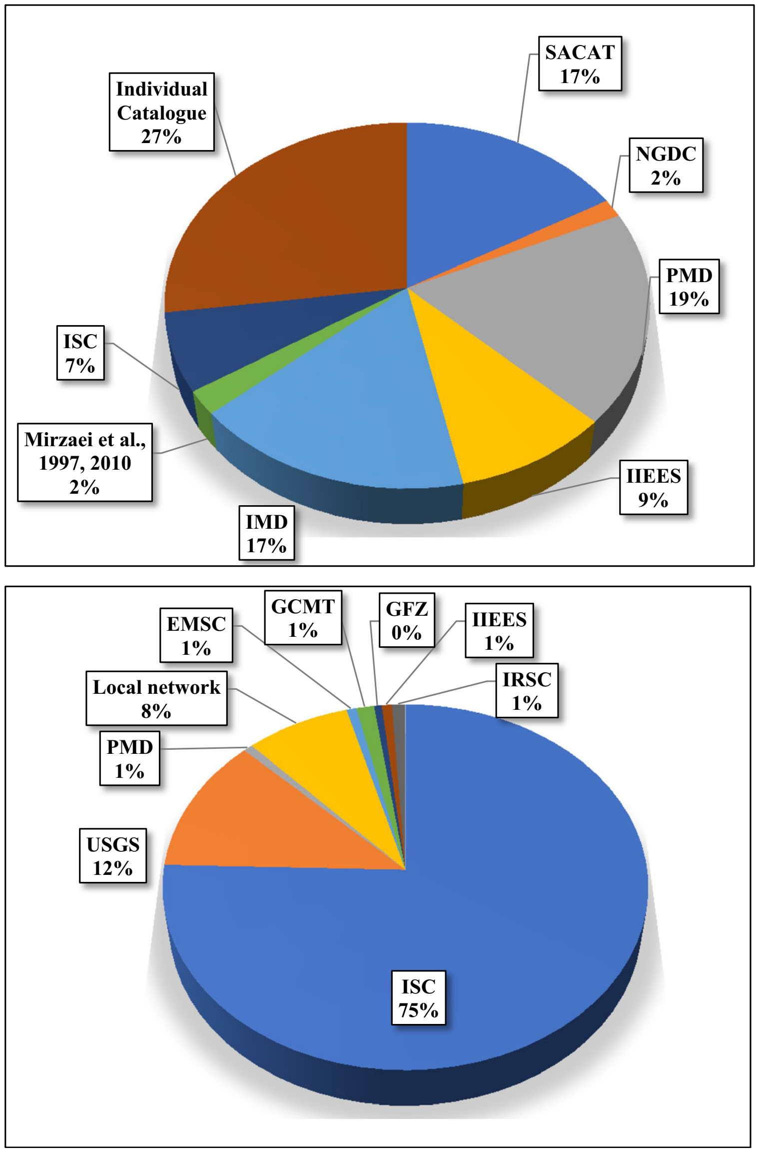


**Fig. 1** Pie chart of the sources contributing to the compilation of the earthquake catalogue (historical is the above figure and instrumental is the below figure)

compiled for the study of the Building Code of Pakistan listed important historical and instrumental earthquakes in the region and was homogenized in moment magnitude up to 2007. However, this catalogue missed several important historical events. Similarly, the work of Zare et al. (2014) is complete only up to 2006 and that of Waseem et al. (2018) is limited to northern Pakistan.

The catalogue compiled in this study is bounded by the geographical limits 40–83° N to 20–40° E around Pakistan. For a reliable PSHA, the consideration of earthquakes from neighbouring countries is necessary. Therefore, during the compilation, earthquakes occurring at least 300 km from the point of interest (Pakistan) were included.

The catalogue was compiled in three phases: (1) prehistorical earthquakes from 25 AD to 1900, (2) historical earthquakes from 1901 to 1964 and (3) instrumental earthquakes from 1965 to 2016. The minimum threshold is set to a moment magnitude of 4.0.

To obtain a unified magnitude (i.e. $M_W$), conversion relationships are developed between moment magnitude and other magnitude scales, which are reported in the available catalogues. The catalogue is processed for the removal of dependent events using a declustering algorithm from Gardner and Knopoff (1974), Uhrhammer (1986), Reasenberg (1985) and Gruenthal (per. comm.). Finally, seismicity parameters for the potential seismic sources in Pakistan are obtained.

## 2 Compilation of data

In the seismic hazard assessment of any area, the first step is to prepare a uniform catalogue that consists of historical and instrumental events.

The region under investigation in this study encompasses a quadrangle bounded by the geographical limits 40°–83° E and 20°–40° N. Prehistorical and historical earthquakes that have occurred in and around Pakistan are compiled from the published literature (e.g. Oldham 1883; Quittmeyer and Jacob 1979; Bilham 1999; Ambraseys 2000; Ambraseys and Bilham 2003a; Ambraseys and Douglas 2004; Bilham and Ambraseys 2005; Bilham et al. 2007; Heidarzadeh et al. 2008; Ambraseys and Bilham 2009; Martin and Szeliga 2010).

The instrumental databanks considered for compilation include the following: the International Seismological Centre (ISC), South Asian Catalog (SACAT), National Earthquake Information Center (NEIC), National Geophysical Data Center (NGDC), World Data Centre (WDCse), India Meteorological Department (IMD) and local networks such as the Pakistan Meteorological Department (PMD), Micro Seismic Studies Program (MSSP), seismic stations of Mangla and Tarbela dams and Water and Power Development Authority (WAPDA) (Fig. 1).

The ISC catalogue contains 25,870 earthquake events in the study region and covers a period from 1918 to 2016. The ISC can be considered the most comprehensive catalogue based on the results of careful and systematic historical investigations. However, the ISC databank alone is not sufficient for a uniform catalogue, as some earthquake events in the region may have been missed in the databank.

Since several sources are used for the earthquake catalogue compilation, the presence of a single event multiple times is possible. Because of this, the priority of earthquake reporting source is set, which is shown in Fig. 2. Tables 1 and 2 list all sources used for data extraction.

## 3 Homogenization

To prepare a uniform catalogue, earthquake events reported at different magnitude scales need to be homogenized to a single scale. In this study, the moment magnitude scale is selected as the representative scale of the catalogue. In this catalogue, earthquake events are reported in $m_b$, $M_S$, $M_W$, $M_L$, Modified Mercalli Intensity (MMI), $M_N$ and $M_D$ magnitude scales. A regression analysis is carried out between the available pairs of moment magnitude and other magnitude scales to develop relationships, as well as to be used for conversion to the moment magnitude scale.

Some historical earthquake events reported in MMI are converted to $M_S$ using Eq. (1) of Ambraseys and Melville (1982).

$$M_S = 0.77 \times I_O - 0.07 \tag{1}$$

Surface wave magnitudes are mostly reported by the NEIC and ISC databanks. Globally, a bilinear trend was observed by Scordilis (2006) between the $M_W$ and $M_S$ magnitude scales, which differentiated low- and high-level magnitudes of $6.2 > M_S \geq 6.2$.

In this study, deviation of $M_S$ corresponding to $M_W$ is observed at an $M_S$ value of 6.0 (Fig. 3). Bilinear relationships [Eqs. (2) and (3)] are established and used to convert $M_S$ to $M_W$. The relationships are derived from 762 paired events of $M_S$ and $M_W$ present in the catalogue.

$$M_W = 0.58 \times M_S + 2.46 \quad \text{for} \quad 3.5 \leq M_S \leq 6.0 \tag{2}$$

$$M_W = 0.94 \times M_S + 0.36 \quad \text{for} \quad 6.1 < M_S \leq 8.2 \tag{3}$$

Earthquake events reported in body wave magnitude scales are converted to moment magnitude using Eq. (4), which is derived from 286 paired events reported in both $m_b$ and $M_W$

$$M_W = 0.93 \times m_b + 0.45 \quad \text{for}\, 4.0 \leq m_b \leq 6.2 \tag{4}$$

Figure 3 shows the linear distribution of $m_b$ and $M_W$ up to an $m_b$ value of 6.2. The trend lines of relationships of surface and body waves are compared (Table 3, Fig. 3) to those of Scordilis (2006), Zare et al. (2014) and Rafi et al. (2012).

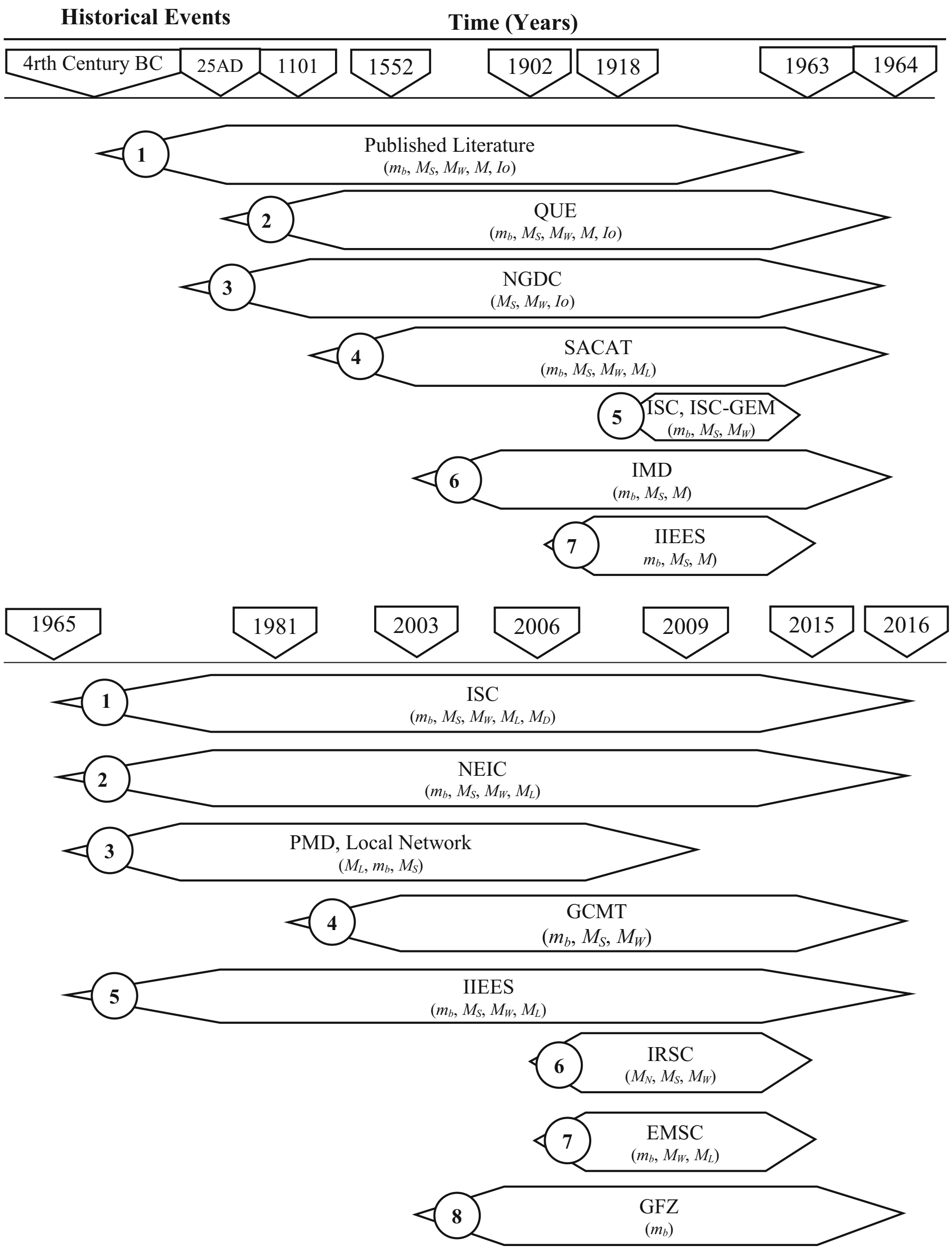


**Fig. 2** Priority order of the historical (above) and instrumental (below) sources used for earthquake catalogue compilation

For $M_L$-type magnitudes, due to a lack of a relationship between paired events, a relation could not be developed between $M_L$ and $M_W$. Therefore, Eq. (5) from Zare et al. (2014) between 2271 paired records of $M_W$ and $M_L$ is used to convert the $M_L$ scale events.

$$M_W = 1.01 \times M_L - 0.05 \quad \text{for } 4.0 \le M_L \le 8.3 \tag{5}$$

The relationship for duration magnitude ($M_D$) and local magnitude ($M_N$) (Nuttli 1973; Rezapour 2005) was also not able to be developed due to

**Table 1** List of sources for the historical and early instrumental catalogue (25 AD–1964)

| Period | Source | $N$ | Magnitude type |
|---|---|---|---|
| 1101–1964 | South Asian Catalog (SACAT) | 371 | $M_S$, $m_b$, $M_W$, $M_L$ |
| 25–1964 | QUE | 377 | $m_b$, $M_S$, $M$, $M_W$, $I_O$ |
| 10–1963 | NGDC | 36 | $M_S$, $M_W$, $I_O$ |
| 1952–1964 | PMD | 46 | $M_L$, $M$ |
| 1902–1963 | IIEES | 213 | $m_b$, $M_S$, $M$ |
| 1552–1963 | IMD | 383 | $M_W$, $M$ |
| 853–1964 | Mirzaei et al. (2002) | 48 | $m_b$, $M_S$, $M$ |
| 1918–1963 | ISC, ISC-GEM | 156 | $m_b$, $M_S$, $M_W$ |
| 1902–1963 | EHB | 21 | $m_b$, $M_S$, $M_W$ |
| 840–1963 | BHRC | 23 | $M_S$, $m_b$, $M_W$ |
| 1505–1945 | Ambraseys and Douglas (2004) | 17 | $M_S$, $M_W$, $I_O$ |
| 1883–1914 | Ambraseys (2000) | 20 | $M_S$, $M_W$ |
| 980–1964 | EMME | 25 | $m_b$, $M_S$, $I_O$ |
| 1779–1872 | Oldham (1883) | 41 | $M_W$, $I_O$ |
| 1911–1963 | WDCse 27 and 40 | 13 | $M_S$ |
| 734–1964 | Ambraseys and Bilham (2009) | 328 | $m_b$, $M_S$, $M_W$, $M$ |
| − 2475–1963 | Ambraseys (2004); Bilham and Lodi (2010); Bilham et al. (2007); Dasgupta et al. (2000); Chandra (1976); Bilham and Ambraseys (2005); Iyengar et al. (1999); Kumar et al. (2001) | 130 | $M_S$, $M_W$, $I_O$ |

$N$ is the number of earthquakes reported by the sources; $M_S$ = surface wave magnitude scale; $m_b$ = body wave magnitude scale; $M_L$ = local magnitude scale; $M_W$ = moment magnitude scale; $Io$ = intensity of earthquake

*EHB* EHB International Seismological Centre (2009); *EMME* Global Earthquake Model for Middle East Report; *IIEES* International Institute of Earthquake Engineering and Seismology; *BHRC* Building and Housing Research Center, Islamic Republic of Iran; *IMD* India Meteorological Department; *PMD* Pakistan Meteorological Department; *QUE* Pakistan Meteorological Department; *ISC* International Seismological Centre; *WDCse* World Data Centre; *NGDC* National Geophysical Data Center

**Table 2** List of sources for the instrumental catalogue (1965–2016)

| Period | Source | $N$ | Magnitude type |
|---|---|---|---|
| 1965–2016 | ISC | 25,714 | $m_b$, $M_S$, $M_W$, $M_L$, $M$, $M_D$ |
| 1965–2016 | NEIC | 4078 | $m_b$, $M_S$, $M_W$, $M_L$ |
| 1965–2016 | PMD | 233 | $M_L$ |
| 1967–2009 | Local network | 2599 | $M_L$, $m_b$, $M_S$ |
| 1999 | Berberian (1994) | 33 | $M_W$ |
| 1977–2016 | BHRC | 38 | $m_b$, $M_S$, $M_W$, $M_L$, $M_N$ |
| 2006–2016 | EMSC | 245 | $m_b$, $M_W$, $M_L$ |
| 1981–2016 | GCMT | 444 | $m_b$, $M_S$, $M_W$ |
| 2003–2016 | GFZ | 191 | $m_b$ |
| 1965–2016 | IIEES | 249 | $m_b$, $M_S$, $M_W$, $M_L$, $M$, $M_{Pv}$ |
| 1966–2007 | IMD | 62 | $M_W$ |
| 2006–2015 | IRSC | 336 | $M_N$, $M$, $M_W$ |

$N$ is the number of earthquakes reported by the sources; $M_S$ = surface wave magnitude scale; $m_b$ = body wave magnitude scale; $M_D$ = duration magnitude; $M_L$ = local magnitude scale; $M_N$ = local magnitude (Nuttli 1973; Rezapour 2005); $M_W$ = moment magnitude; $I_O$ = MMI of earthquake

*NEIC* National Earthquake Information Center; *IIEES* International Institute of Earthquake Engineering and Seismology; *BHRC* Building and Housing Research Center, Islamic Republic of Iran; *IMD* India Meteorological Department; *PMD* Pakistan Meteorological Department; *ISC* International Seismological Centre; *IRSC* Iran Seismological Centre; *GCMT* Global Centroid Moment Tensor database; *EMSC* European-Mediterranean Seismological Centre; *GFZ* GEOFON Global Seismic Network, Helmholtz-Zentrum, Potsdam

absence of paired events. There are 22 events reported in $M_D$ and 355 in $M_N$. The relations [Eqs (6) and (7)] of Kaviris et al. (2008) are adopted in this study to convert $M_D$ to $M_W$, and Eq. (8) of Karimiparidari et al. (2013) is used for $M_N$ conversion to $M_W$.

$$M_W = 0.5 \times M_D \quad \text{for}\, M_D < 3.0 \tag{6}$$

$$M_W = 0.6 + M_D \quad \text{for}\, 3.0 \leq M_D \tag{7}$$

$$M_W = 0.739 \times M_N + 1.409 \quad \text{for}\, 3.5 \leq M_N \leq 6.3. \tag{8}$$

## 4 Data processing

To construct the catalogue, the magnitude is entered in a priority order of $M_W$, $m_b$, $M_S$, $M_L$, $I_O$, $M_N$ and $M_D$. The

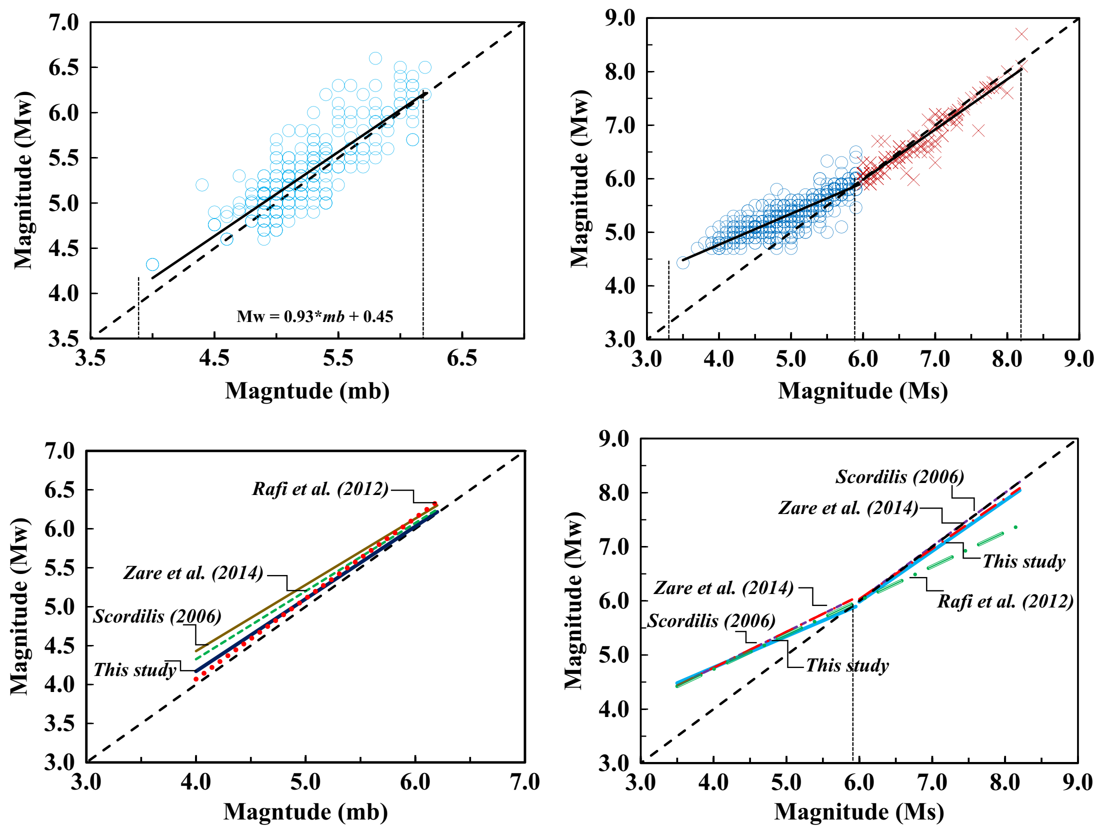


**Fig. 3** Relationships developed between $m_b \rightarrow M_W$ and $M_S \rightarrow M_W$

major data reporting eras are shown in Figs. 2 and 4 with the reporting events. Events with zero magnitudes are excluded from the catalogue. Additionally, duplicate events occurring on the same date, hour and minute within an epicentral distance of 30 km are manually removed.

After the homogenization, the catalogue consists of 36,563 events (Fig. 5). This catalogue contains events in

**Table 3** Comparison of magnitude error with Zare et al. (2014) and Scordilis (2006) and conversions from $m_b$ to $M_W$ and from $M_S$ to $M_W$

| Type of magnitude | Conversion relation | Boundary | $R^2$ | Numbers | Standard deviation ($\sigma$) | Study |
|---|---|---|---|---|---|---|
| $m_b$, $M_W$ | $M_W = 0.93 \times m_b + 0.45$ | $4.0 \le m_b \le 6.2$ | 0.71 | 286 | 0.18 | This study |
| | $M_W = 0.87 \times m_b + 0.83$ | $3.5 \le m_b \le 6.0$ | 0.88 | 16,752 | 0.30 | Zare et al. (2014) |
| | $M_W = 0.85(\pm 0.04) \times m_b + 1.03(\pm 0.23)$ | $3.5 \le m_b \le 6.2$ | 0.53 | 39,784 | 0.29 | Scordilis (2006) |
| | $M_W = 1.04 \times m_b - 0.07$ | $4.0 \le m_b \le 6.9$ | 0.72 | | | Rafi et al. (2012) |
| $M_S$, $M_W$ | $M_W = 0.58 \times M_S + 2.46$ | $3.5 \le M_S < 6.0$ | 0.75 | 597 | 0.07 | This study |
| | $M_W = 0.94 \times M_S + 0.36$ | $6.0 \le M_S \le 8.2$ | 0.91 | 165 | 0.15 | |
| | $M_W = 0.66 \times M_S + 2.11$ | $2.8 \le M_S \le 6.1$ | 0.94 | 4123 | 0.28 | Zare et al. (2014) |
| | $M_W = 0.93 \times M_S + 0.45$ | $6.2 \le M_S \le 8.2$ | 0.88 | 129 | | |
| | $M_W = 0.67(\pm 0.005) \times M_S + 2.07(\pm 0.03)$ | $3.0 \le M_S \le 6.1$ | 0.77 | 23,921 | 0.17 | Scordilis (2006) |
| | $M_W = 0.99(\pm 0.02) \times M_S + 0.08(\pm 0.13)$ | $6.2 \le M_S \le 8.2$ | 0.81 | 2382 | 0.2 | |
| | $M_W = 0.63 \times M_S + 2.21$ | $3.5 \le M_S \le 8.0$ | 0.84 | | | Rafi et al. (2012) |

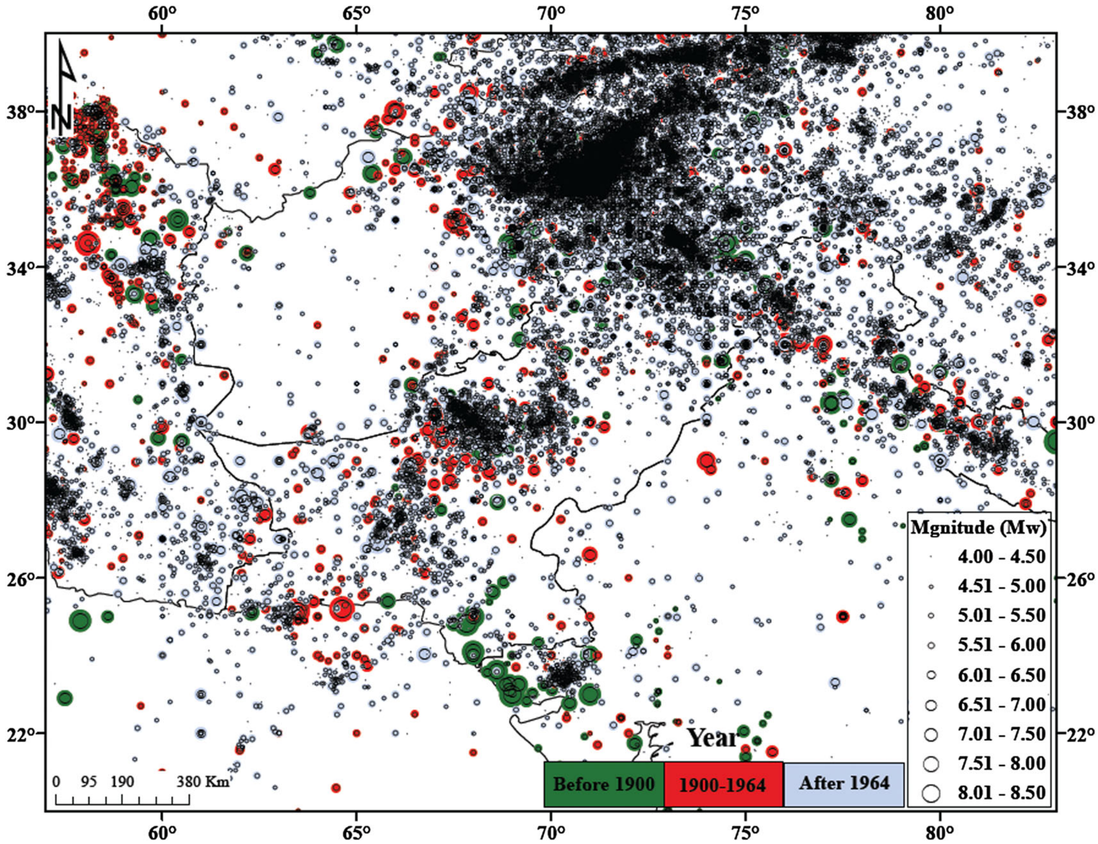


**Fig. 4** Temporal distributions of the earthquakes in the catalogue

moment magnitude (4.0–8.3) from the year 25 AD to 2016.

Based on the focal depths of earthquakes, the catalogue is divided into deep and shallow earthquakes (Figs. 6 and 7). Figure 8 shows historical and instrumental earthquakes of magnitude > 6.5, which are described in the Appendix.

## 5 Declustering

Earthquake seismicity (space-time correlation) is generally exhibited by foreshock and aftershock events; therefore, statistical modelling is necessary to identify the independent occurrence of the main shocks. Space-time windowing techniques are normally used for this purpose (e.g. Uhrhammer 1986; Knopoff et al. 1982; Gardner and Knopoff 1974; Reasenberg 1985).

In this work, earthquake events are declustered using four algorithms from Gardner and Knopoff (1974), Gruenthal (pers. comm.), Uhrhammer (1986) and Reasenberg (1985) in Z-Map (Wiemer 2001). Each algorithm considers different time and distance ranges for declustering. An approximation of window sizes according to Gardner and Knopoff (1974), Gruenthal (pers. comm.) and Uhrhammer (1986) is shown in Table 4. The default standard parameter values of Reasenberg's algorithm are given in Table 5.

The declustered catalogue using the Gardner and Knopoff (1974), Gruenthal (pers. comm.), Uhrhammer (1986) and Reasenberg (1985) algorithms contains 8579, 5344, 18,754 and 31,856 events, respectively (Table 6). The declustered catalogue using the Gardner and Knopoff (1974) algorithm is selected for computation of hazard value parameters.

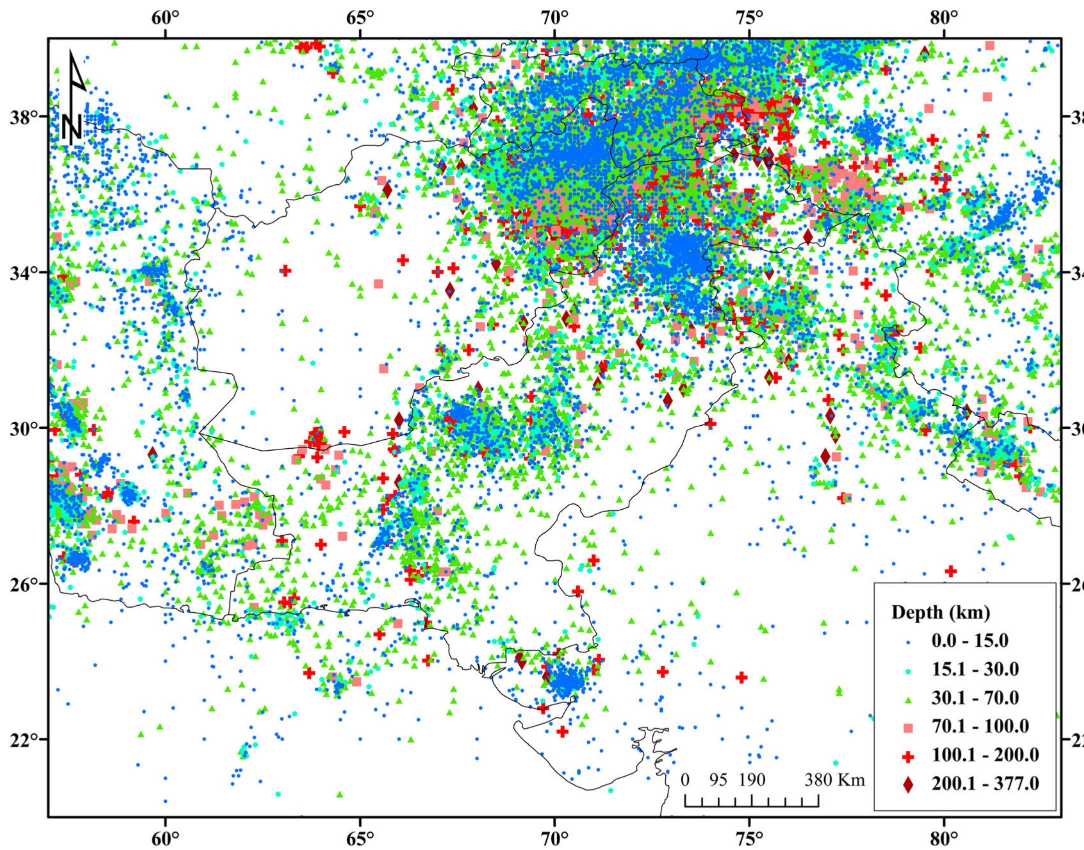


**Fig. 5** Distribution of focal depths of events in the catalogue

## 6 Magnitude uncertainties and data completeness

In the study region, prehistorical records (prior to 1900) are somewhat insignificant. The NGDC database has listed prehistorical earthquakes but suffers from data inconsistencies (Dunbar et al. 1992). Quittmeyer and Jacob (1979) and Martin and Szeliga (2010) presented a catalogue based on the data of macroseismic intensity for events occurring as early as 1636 in Pakistan and surrounding regions. The data is completed for larger magnitudes (> 8.0) and for larger periods (1800) (Szeliga et al. 2010). In their study, higher uncertainty associated with the magnitude and location of an earthquake is estimated using macroseismic intensity data. The historical events (1900–1964) are compiled by consulting several relevant online publications that report earthquakes in magnitude scales of $m_b$, $M_S$ and $M_W$ (Tables 1 and 2), e.g. Lee et al. (1976), Chandra (1977), Bapat et al. (1983), Dunbar et al. (1992), Bilham (1995, 1999), Rao (2000), Ambraseys (2000), Rajendran and Rajendran (2001), Ambraseys and Jackson (2003), Ambraseys and Bilham (2003b), Ambraseys and Douglas (2004), Jaiswal and Sinha (2004), Bilham et al. (2005), Bilham and Ambraseys (2005), Okal and Synolakis (2008) and Amateur Seismic Centre (2009).

In the Afghanistan region, Ambraseys and Bilham (2003a) have also projected $M_S$ values for the historical record, which is based on an apparent intensity of destruction.

The occurrence of some historical earthquakes does not have adequate evidence (e.g. Szeliga et al. 2010; Bapat et al. 1983; Heidarzadeh et al. 2008). In the Makran region, unknown (magnitude/intensity) historical earthquakes are reported by Heidarzadeh et al. (2008) during 326 BC, 1008, 1483, 1668, 1765 and 1851.

For the compilation of main shocks in the instrumental data (1964–2016), the distribution of prominent errors indicates 0.18 units for $m_b$ entries and 0.07 units for $M_S$ (Table 3). The homogenous earthquake catalogue of

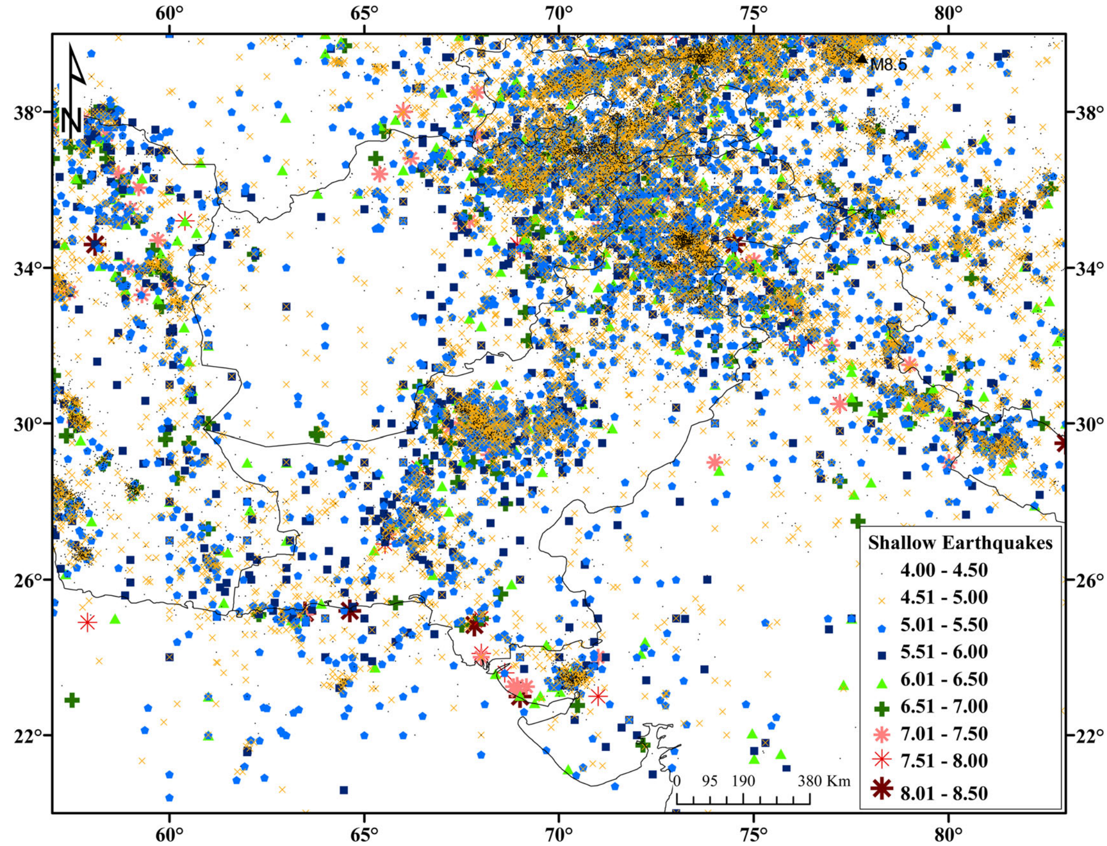


**Fig. 6** Earthquake (focal depth ≤ 50 km) spatial distribution

Pakistan in the $M_W$ scale and the description of the sources are attached to this manuscript as supplementary material.

## 7 Magnitude of completeness

Determination of the magnitude of completeness ($M_C$) is an important parameter for studying seismic hazards. The $M_C$ values reported for Pakistan along with potential seismic sources are shown in Fig. 9. Minimum and maximum magnitudes of completeness observed in the region are $M_C$ 4.0 for source 4 and $M_C$ 5.3 for source 5 (Table 7). The completion magnitude in Hindu Kush, Islamabad, Peshawar, western Makran and south of the Karachi region is observed to be $M_C$ 4.4 and $M_C$ 5.5 in the Punjab Plain, Gwadar and Quetta regions (Fig. 9). The completion magnitude over time from 1975 to 2016 for Pakistan is shown in Fig. 10.

## 8 Seismicity parameters

The study region (Pakistan) is divided into 20 major seismic sources (shallow and deep) based on seismicity data and regional tectonics (Figs. 11 and 12). The deep source delineation is taken from Waseem et al. (2018). For these seismic sources, the $b$ value is estimated using the maximum likelihood method proposed by Aki (1965). This method is based on a theoretical consideration that gives an estimate of $b$ value (Eq. (9)) with a modified (Shi and Bolt 1982) standard deviation error $\delta b$ (Eq. (10)).

$$b = \frac{\log_{10} e}{M - M_0} \tag{9}$$

$$\delta b = 2.3 b^2 \sqrt{\frac{\sum (M_i - M)}{n(n-1)}} \tag{10}$$

where $M_0$ is the threshold; $M_i$ and $M$ are the magnitude of the $i$th event and the average

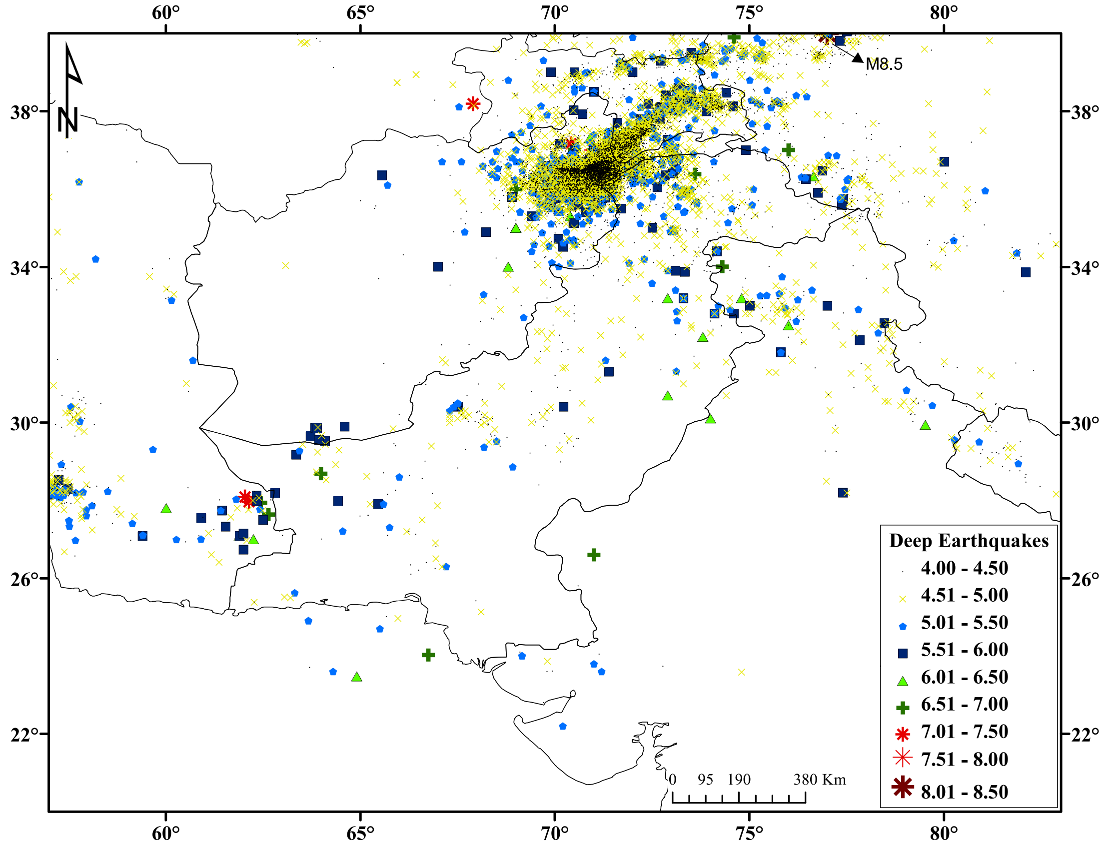


**Fig. 7** Earthquake (focal depth > 50 km) spatial distribution

magnitude, respectively; and *n* is the earthquake number in the set.

The computations are completed in Z-Map (Wiemer 2001). The estimated Gutenberg and Richter (1944) parameters *a* and *b* are shown in Table 7 for shallow and deep seismic sources (Fig. 13 and 14). The *b* value varies from 0.536 to 1.380 for all seismic sources. The maximum activity rate is observed in source 15 (i.e. 35.809) with a *b* value of 0.969 and a maximum magnitude ($M_W$) of 7.5.

## 9 Discussion and conclusions

A homogenized earthquake catalogue is compiled and presented for Pakistan, which is a very useful tool for carrying out seismic hazard assessment studies. To compile the earthquake catalogue, all available sources including international online data reporting agencies, local reporting networks and individual catalogues have been consulted. The compiled catalogue is homogenized in terms of moment magnitude and reports 36,563 events with a magnitude range ($M_W$) of 4.0 to 8.3, which is bounded by the geographical limits 40–83° N and 20–40° E. Indigenous relationships are developed between $m_b$, $M_S$ and $M_W$ and used for the homogenization. The catalogue is processed for completeness and removal of dependent events for regional seismic hazard assessment studies. The declustering (i.e. removal of dependent events) is performed following Gardner and Knopoff (1974), Uhrhammer (1986), Reasenberg (1985) and Gruenthal (per. comm.) algorithms from Z-Map (Wiemer 2001). These declustering algorithms confirms the existance of epistemic uncertainty to be considered in seismic hazard analysis for Pakistan. The declustered catalogue based on these algorithms is further processed to compute parameters of the Gutenberg and Richter (1944) relationship for 20 potential seismic sources (deep and shallow) in Pakistan. The minimum completion magnitude (Fig. 9) ($M_C$) of 4.4 is observed in the western Makran and Hindu Kush regions.

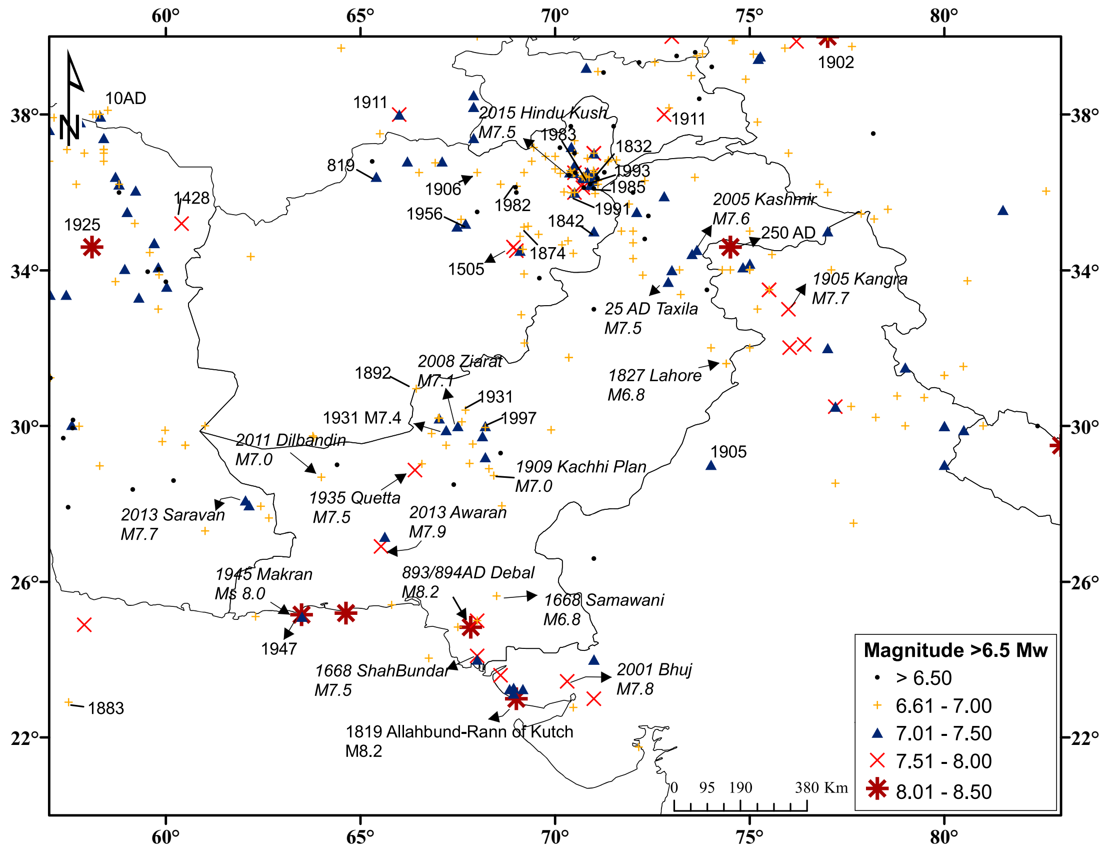


**Fig. 8** Earthquake (6.5) spatial distribution

For shallow seismic sources, the activity rate varies from 0.376 to 35.809 in comparison to deep seismic sources that vary from 2.032 to 16.569. Shallow source 4 is interpreted as the least active seismic region with an activity rate of 0.376 compared to the other seismic sources. In this source, 15 earthquakes (maximum magnitude ($M_W$) is 6.4) are reported.

The capital of Pakistan, Islamabad, lies within shallow source 18 (Fig. 12) and deep source 8 (Fig. 12). In source 18, the maximum magnitude ($M_W$) of 6.5 is observed with an activity rate of 2.409 and a $b$ value of 0.797. In source 8, the maximum magnitude ($M_W$) of 7.4 is observed with an activity rate of 6.886 and a $b$ value of 0.733. This leads to the conclusion that in the Islamabad region, shallow earthquakes contribute more compared to deep earthquakes. Conversely, in the Hindu Kush region, deep earthquakes (source 16 of Fig. 12) added more to the activity rate compared to shallow earthquakes (source 1 of Fig. 11) and contributed more to the seismic hazard.

**Table 4** An approximation of the window sizes according to Gardner and Knopoff (1974), Gruenthal (pers. comm.) and Uhrhammer (1986)

| Method | Distance (km) | Time (days) |
|---|---|---|
| Gardner and Knopoff (1974) | $10^{0.1238M+0.983}$ | $10^{0.032M+2.7389}$ if $M \geq 6.5$<br>$10^{0.5409M-0.547}$, else |
| Gruenthal (pers. comm.) | $10^{1.77+(0.037+1.02M)^{2}}$ | $\left\lvert e^{-3.95+(0.62+17.32M)^{2}} \right\rvert$ if $M \geq 6.5$<br>$10^{2.8+0.024M}$, else |
| Uhrhammer (1986) | $e^{-1.024+0.804M}$ | $e^{-2.87+1.235M}$ |

Table 5 Default standard parameters of Reasenberg's algorithm

| Parameter | Standard | Simulation range | |
|---|---|---|---|
| | | Min | Max |
| $\tau_{min}$ [days] | 1 | 0.5 | 2.5 |
| $\tau_{max}$ [days] | 10 | 3 | 15 |
| $P$ | 0.95 | 0.9 | 0.99 |
| $x_{meff}$ | 4.0 | 0 | 1 |
| $x_k$ | 0.5 | 1.6 | 1.8 |
| $r_{fact}$ | 10 | 5 | 20 |

In the Gwadar and western Makran regions, a deep earthquake of $M_W$ 7.5 is observed in source 20 (Fig. 12), but the activity rate is still 7.8% higher due to shallow earthquakes.

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## Appendix. Description of some large earthquakes

Prehistorical earthquakes

*25 AD, Taxila earthquake* An earthquake of Modified Mercalli Intensity IX (Khan and Khan 2016) occurred at Taxila, 25 km west-northwest of Islamabad, which destroyed Buddhist monasteries.

*June 819, Afghanistan earthquake (M = 7.4)* This earthquake destroyed Balk City and the Masjid-i Jami (Ambraseys and Bilham 2009).

*893/894, Debal earthquake (M = 7.5)* Earthquake of Richter magnitude 7.5 occurred between 13 March 893 AD and 14 December 894 AD, causing massive damage (150,000 deaths) to the town of Debal (lower Sindh) (Gates and Ritchie 2006).

*6 July 1505, Paghman, Afghanistan, earthquake* This earthquake struck in Paghman with an intensity of IX to X (MM). It ruptured the northern portion of the Chaman fault (Quittmeyer and Jacob 1979).

*2 May 1668, Shah Bundar earthquake* An event of magnitude 7.0 to 7.6 occurred near the Shah Bundar area of lower Sindh on 2 May 1668 (Pervaiz et al. 2002). No destruction/damage records were found in the Thatha historical records. The epicentre was someplace west of the Kuch Rift. Only Shah Bundar was affected by shockwaves, and permanent ground displacement occurred.

*May 1688, near Shah Bundar* This event is not registered in detail, but it is said that it has occurred in the same area where the 2 May 1668 event of magnitude 7.0 to 7.6 was felt.

*16 June 1819, Rann of Kutch (Allah Bund), India, earthquake* An earthquake of magnitude 7 to 7.8 and intensity IX to X+ (MM) occurred approximately 50 km northeast of the town of Bhuj (Pervaiz et al. 2002). A high fault scarp known as Allah Bund, which trends east-west, dammed Shatadro stream (Oldham 1926).

*26 September 1827, near Lahore* This earthquake is listed in few catalogues, and its epicentre was at 31.60° N, 74.30° E. A total loss of life of at least 1000 was recorded in Lahore and other parts of Punjab (Quittmeyer and Jacob 1979).

Table 6 Clustered and declustered event results from the four algorithms

| Type of method | Number of events | Number of clusters | Number of events in final catalogue | Number of events out of catalogue (%) |
|---|---|---|---|---|
| Gardner and Knopoff (1974) | 36,563 | 3509 | 8579 | 27,984 (76.54) |
| Uhrhammer (1986) | | 3868 | 18,754 | 17,809 (48.71) |
| Reasenberg (1985) | | 1731 | 31,856 | 6438 |
| Gruenthal (pers. comm.) | | 2737 | 5344 | 31,219 (85.38) |

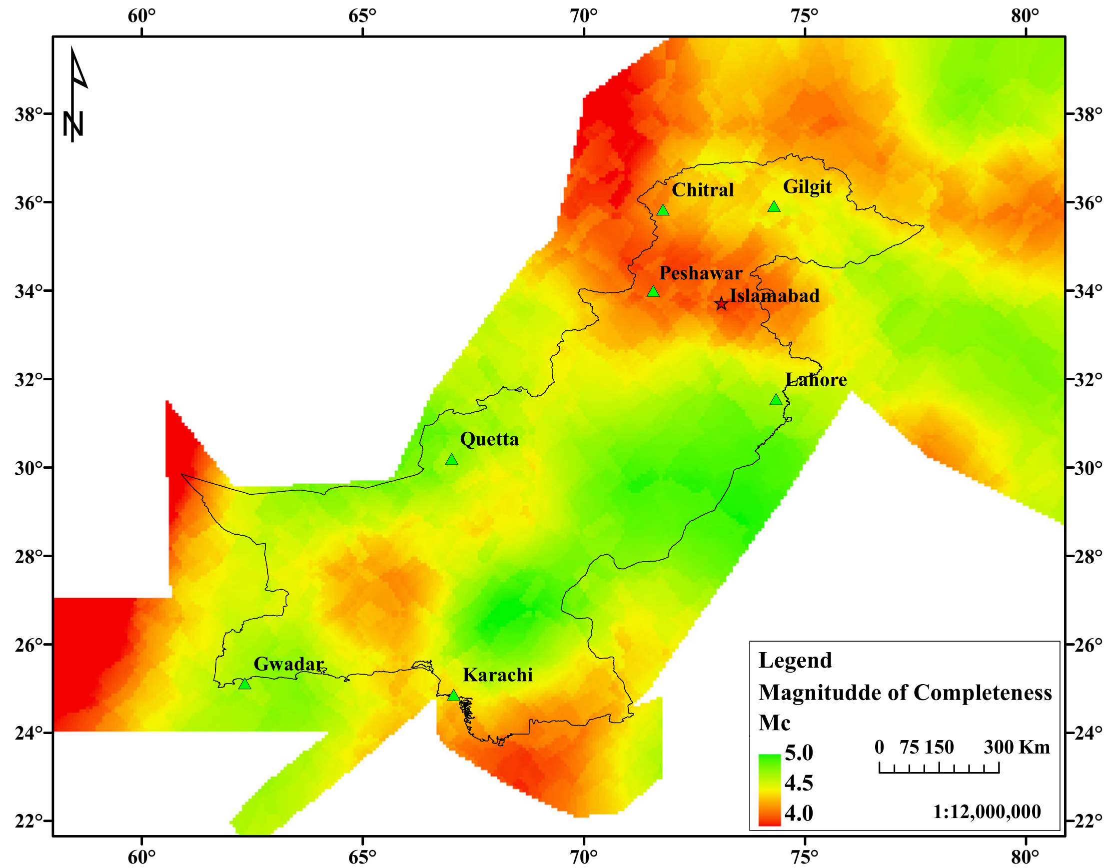


**Fig. 9** The $M_C$ values reported for Pakistan along with the potential seismic sources

*22 January 1832, Badakhshan earthquake* This was a great earthquake (epicentral intensity = IX; $m_b = 7.4$) and apparently killed thousands of people and ruined a most of the villages in the district.

*19 February 1842, Alingar Valley, Afghanistan, earthquake* This earthquake ($M_S$ 7.5) severely affected the Alingar River Valley and the Jalalabad Basin in Afghanistan, killing hundreds of people (Quittmeyer and Jacob 1979). Contemporary narratives indicate that a rupture proceeded from north-northeast to south-southwest along a portion of the Gardez fault, which is situated in the Alingar River Valley.

*October 1874 ($M_S \approx 7.0$)* This earthquake occurred near the northern boundary of the Paghman fault. The north Kabul region was greatly affected during this earthquake (Ambraseys and Bilham 2009). In the vicinity of Jabal Saraj, the surface opened up, which was likely due to liquefaction.

*1883, Jhalawan (Pakistan) earthquake* The epicentre of this earthquake was at Jhalawan with a magnitude of 8.0.

*20 December 1892, Chaman earthquake (MM = XIII to IX)* The event occurred 90 km northwest of Quetta near the border of Afghanistan and Pakistan (Quittmeyer and Jacob 1979). During this earthquake, left lateral strike-slip movement of at least 75 cm occurred on the Chaman fault near the town of Sanzal.

Historical earthquakes

*4 April 1905, Kangra, India, earthquake* A magnitude of 8 ($M_S$) was determined for this event (Geller and Kanamori 1977; Gutenberg and Richter 1954) with a maximum intensity of X+ (MM). This earthquake killed 19,000 people and caused heavy damage to towns along the foothills of the Himalayas between Kangra and Dehra Dun.

**Table 7** Seismicity parameters for 20 seismic sources obtained using the maximum likelihood method of Aki (1965)

| No. | Zones | Events | $M_{Wmin}$ | $M_{Wmax}$ | $D_{Max}$ (km) | $D_{Min}$ (km) | SOY | EOY | *a* value | *b* value | $M_C$ | Lambda |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Zone 1 | 403 | 4 | 7 | 50 | 0 | 1975 | 2016 | 3.8 | 0.669 | 4.4 | 13.310 |
| 2 | Zone 2 | 270 | 4 | 7 | 49.8 | 0 | 1975 | 2016 | 3.62 | 0.657 | 4.4 | 9.817 |
| 3 | Zone 3 | 49 | 4 | 7.4 | 49 | 0 | 1975 | 2016 | 3.31 | 0.719 | 4.7 | 2.716 |
| 4 | Zone 4 | 15 | 4 | 6.4 | 47 | 0 | 1975 | 2014 | 1.72 | 0.536 | 4 | 0.376 |
| 5 | Zone 5 | 55 | 4 | 6.7 | 39 | 0 | 1975 | 2016 | 6.93 | 1.38 | 5.3 | 25.703 |
| 6 | Zone 6 | 459 | 4 | 7.5 | 49.9 | 0 | 1975 | 2016 | 4.98 | 0.892 | 4.7 | 25.827 |
| 7 | Zone 7 | 60 | 4 | 6.9 | 35 | 0 | 1975 | 2016 | 2.42 | 0.554 | 4.1 | 1.599 |
| 8 | Zone 8 | 197 | 4 | 7.4 | 50 | 0 | 1975 | 2016 | 3.77 | 0.733 | 4.4 | 6.886 |
| 9 | Zone 9 | 273 | 4 | 7 | 49.1 | 0 | 1976 | 2016 | 4.95 | 0.923 | 4.7 | 18.113 |
| 10 | Zone 10 | 139 | 4 | 6.8 | 50 | 0 | 1975 | 2016 | 4.82 | 0.942 | 5.0 | 11.271 |
| 11 | Zone 11 | 479 | 4 | 7.1 | 46.6 | 0 | 1975 | 2016 | 4.44 | 0.787 | 4.4 | 19.588 |
| 12 | Zone 12 | 69 | 4 | 7.8 | 48 | 0 | 1976 | 2015 | 3.41 | 0.746 | 4.5 | 2.666 |
| 13 | Zone 13 | 43 | 4.1 | 5.9 | 44.8 | 0 | 1976 | 2016 | 6.06 | 1.29 | 4.9 | 5.902 |
| 14 | Zone 14 | 337 | 4 | 7.9 | 50 | 0 | 1975 | 2016 | 4.76 | 0.875 | 4.7 | 18.197 |
| 15 | Zone 15 | 564 | 4 | 7.5 | 50 | 0 | 1975 | 2016 | 5.43 | 0.969 | 4.7 | 35.809 |
| 16 | Zone 16 | 459 | 4 | 7.5 | 456 | 51 | 1975 | 2016 | 4.16 | 0.735 | 4.4 | 16.595 |
| 17 | Zone 17 | 95 | 4.1 | 6 | 289 | 51.4 | 1975 | 2016 | 4.67 | 1.02 | 4.4 | 3.076 |
| 18 | Zone 18 | 50 | 4 | 6.5 | 589 | 51 | 1975 | 2016 | 3.57 | 0.797 | 4.9 | 2.409 |
| 19 | Zone 19 | 52 | 4.1 | 6.7 | 372 | 51 | 1975 | 2015 | 4.1 | 0.906 | 4.6 | 2.428 |
| 20 | Zone 20 | 70 | 4.1 | 7.5 | 185.9 | 51 | 1975 | 2016 | 2.85 | 0.62 | 4.4 | 2.032 |

Activity rate (lambda) is estimated using the log (lambda) = $a - b \times M_{Wmin}$ relationship of Gutenberg and Richter (1944)

*24 October 1906, Afghanistan earthquake* This was a widely felt earthquake (*M* 7.1) with an epicentre on the border of Afghanistan and Uzbekistan (Ambraseys and Bilham 2009). The earthquake waves were felt as low intensities within a radius of approximately 380 km and only felt strongly at Aivadz and Termez.

*21 October 1909, Kachhi Plain (between Loralai and Sibi), Pakistan, earthquake* This earthquake reached a

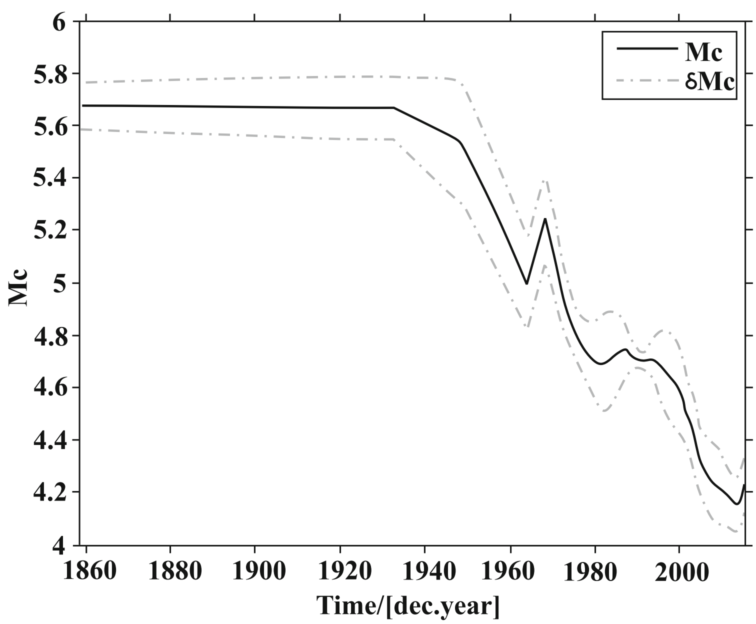


**Fig. 10** Complete magnitudes over time for Pakistan

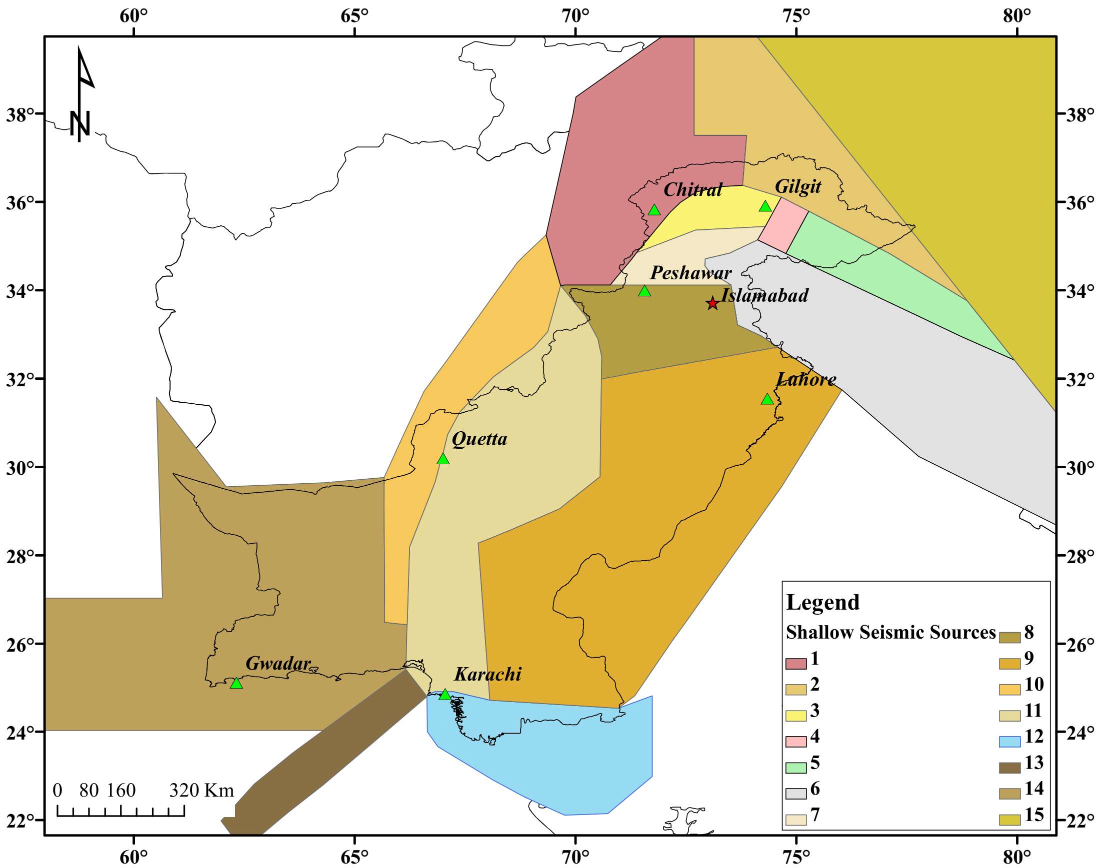


**Fig. 11** Shallow seismic sources divided based on seismicity data for Pakistan

maximum intensity of VIII to IX (MM) in a zone that extended southeastward from north of Bagh to southeast of Shahpur. Numerous small villages were destroyed, and more than 100 lives were lost (Quittmeyer and Jacob 1979).

*7 July 1909 (≈ 7.5)* This earthquake was globally documented and may have contained two events: one shallow and the other deep (1 min apart).

*1 February 1929, between Buner and Hazara, Pakistan* This earthquake occurred north of Abbottabad (MM 8.0) around a local time of 10:45 pm (Quittmeyer and Jacob 1979).

*24 August 1931, Sharigh, Pakistan, earthquake* This was a very shallow focused earthquake. The epicentre of this earthquake is located at 30.38° N, 67.68° E, approximately 75 km east-northeast of Quetta, and an $M_S$ 7.0 (Gutenberg and Richter 1954) and intensity of 8.0 (Quittmeyer and Jacob 1979) were given to this earthquake.

*27 August 1931, Mach, Pakistan, earthquake* The epicentre of the Mach earthquake is located at 29.91° N, 67.25° E near the town of Mach and approximately 50 km southeast of Quetta (Ambraseys and Bilham 2003a). This was the second earthquake over the course of 2 days with an $M_S$ of 7.4 (Gutenberg and Richter 1954) that affected the same region. It was more devastating than the 25 August 1931 earthquake, which was felt in most of Baluchistan and Sindh (Quittmeyer and Jacob 1979).

*30 May 1935, Quetta, Pakistan, earthquake* The epicentre of this magnitude $M_S$ 7.5 (Gutenberg and Richter 1954) earthquake is located at 28.87° N, 66.40° E. The city of Quetta was ruined, and approximately 30,000 lives were lost (Richter 1958). A

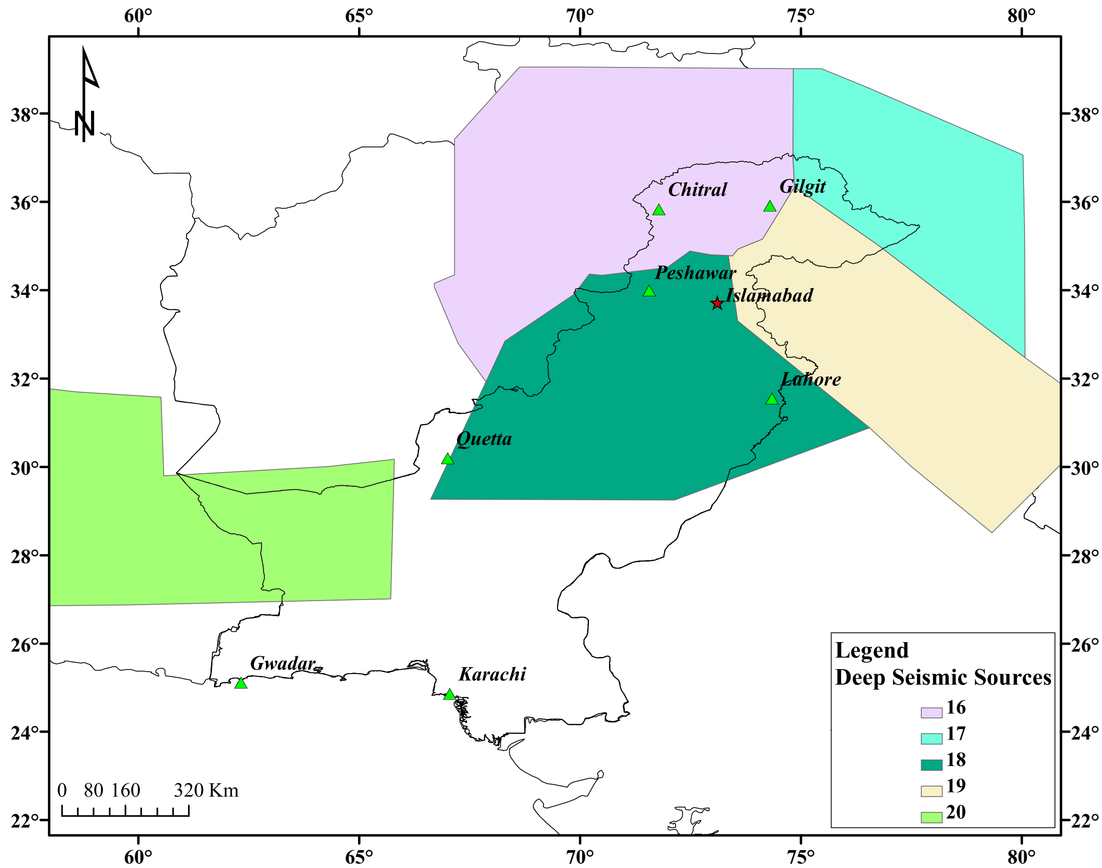


**Fig. 12** Deep seismic sources divided based on seismicity data for Pakistan

maximum intensity of IX to X RF (~IX to X MM) was confined to a narrow, elongated zone trending parallel to the local structure and extending from Quetta to south of Mastung.

*21 November 1939, Badakhshan Province, Afghanistan* This earthquake had a magnitude $M_S$ of 6.9 (NOAA) and was felt in much of northern Pakistan, all over northeastern Afghanistan and northern India. An epicentral intensity value of VIII was documented in the Gilgit and Drosh regions (Ambraseys and Bilham 2009).

*27 November 1945, Makran Coast, Pakistan, earthquake* The epicentre of this event is located at 25.15° N, 63.48° E, which is just off the Makran Coast of Pakistan near the town of Pasni. Geller and Kanamori (1977) found that it was a 20-s earthquake of $M_S$ 8.0, which also generated a tsunami along the coast. An intensity of X (MM) reached at Pasni and Ormara (International Seismological Summary 1945). A total life loss of 2000 was noted in neighbouring Iran and southern Pakistan. Damage also occurred at Ormara (Quittmeyer and Jacob 1979).

*5 August 1947* Another large event with a surface wave magnitude of 7.3 (Gutenberg and Richter 1954) occurred at nearly the same location as the 1945 event (Ambraseys and Bilham 2003a). Nothing more is known of this second large Makran earthquake.

*9 June 1956, Sayghan, Afghanistan, earthquake* A large magnitude earthquake (20 s, $M_S$ 7.6) occurred in the Bamyan District, Afghanistan. This event, which caused the deaths of 300 to 400 people (Heuckroth and Karim 1970), has an epicentre at 35.13° N, 67.48° E, near Sayghan, Afghanistan (Ambraseys and Bilham 2009).

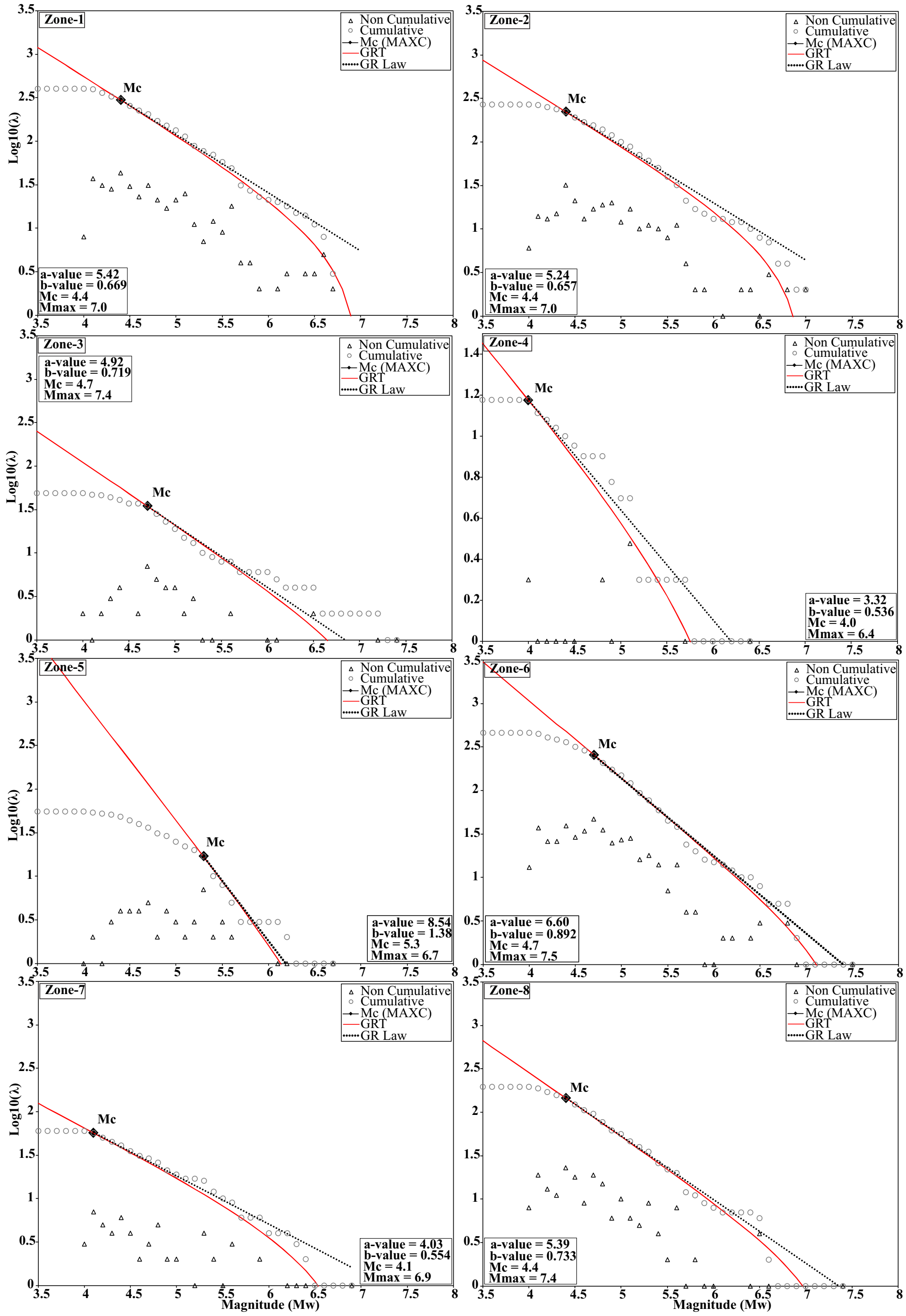


**Fig. 13** Cumulative curve with complete magnitudes for shallow seismic sources. Seismicity parameters, i.e. b values, are estimated using the maximum likelihood method of Aki (1965). Blank circles represent cumulative data, and triangles show non-cumulative data

Modern earthquakes

*December 1983, Hindu Kush, Afghanistan* The shock ($M_W$ 7.40, depth 215 km) was felt in much of northwestern Afghanistan, Tajikistan, Uzbekistan, Kyrgyzstan, northern Pakistan and northern India. Fourteen additional deaths occurred in Peshawar, Pakistan.

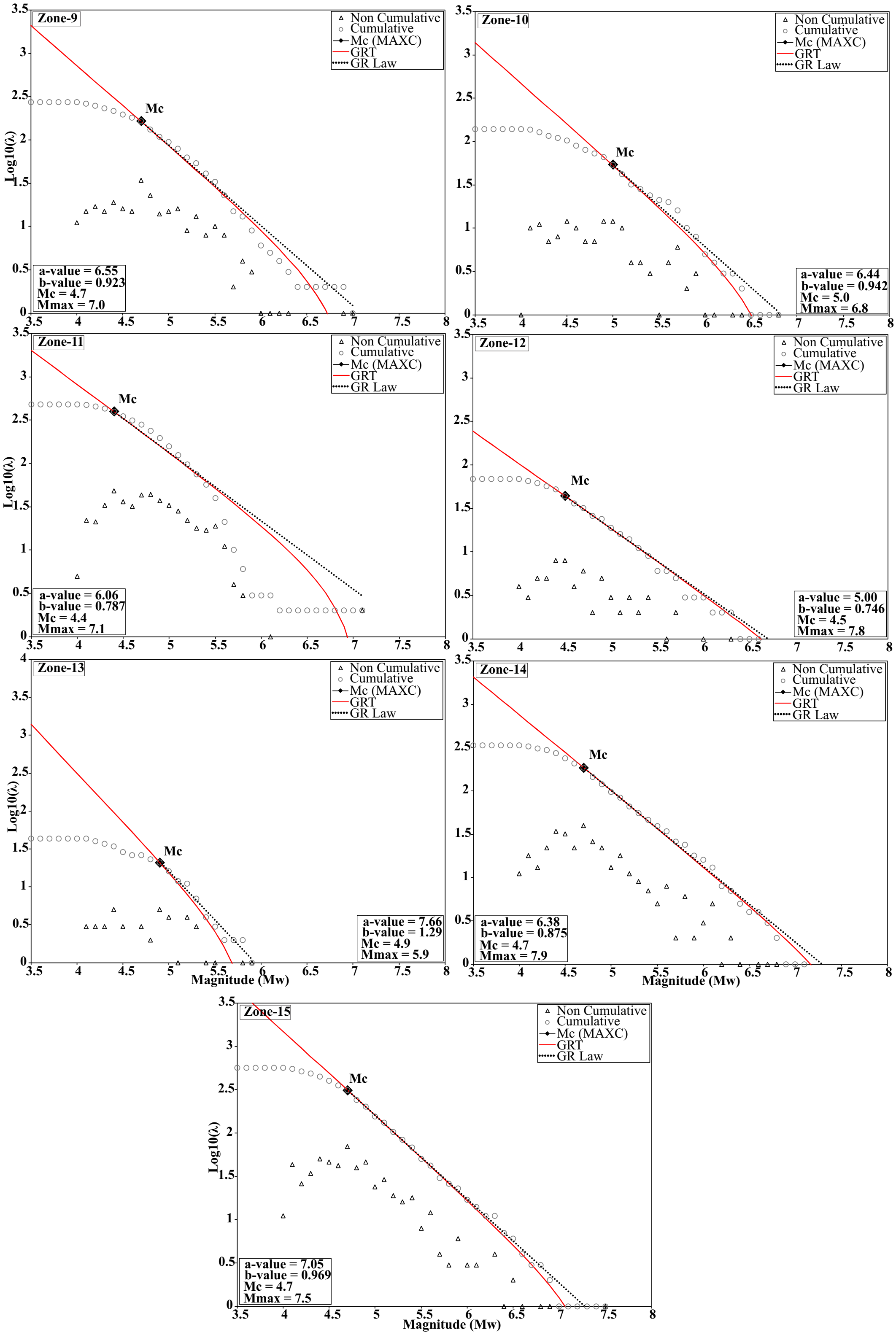


**Fig. 13** continued.

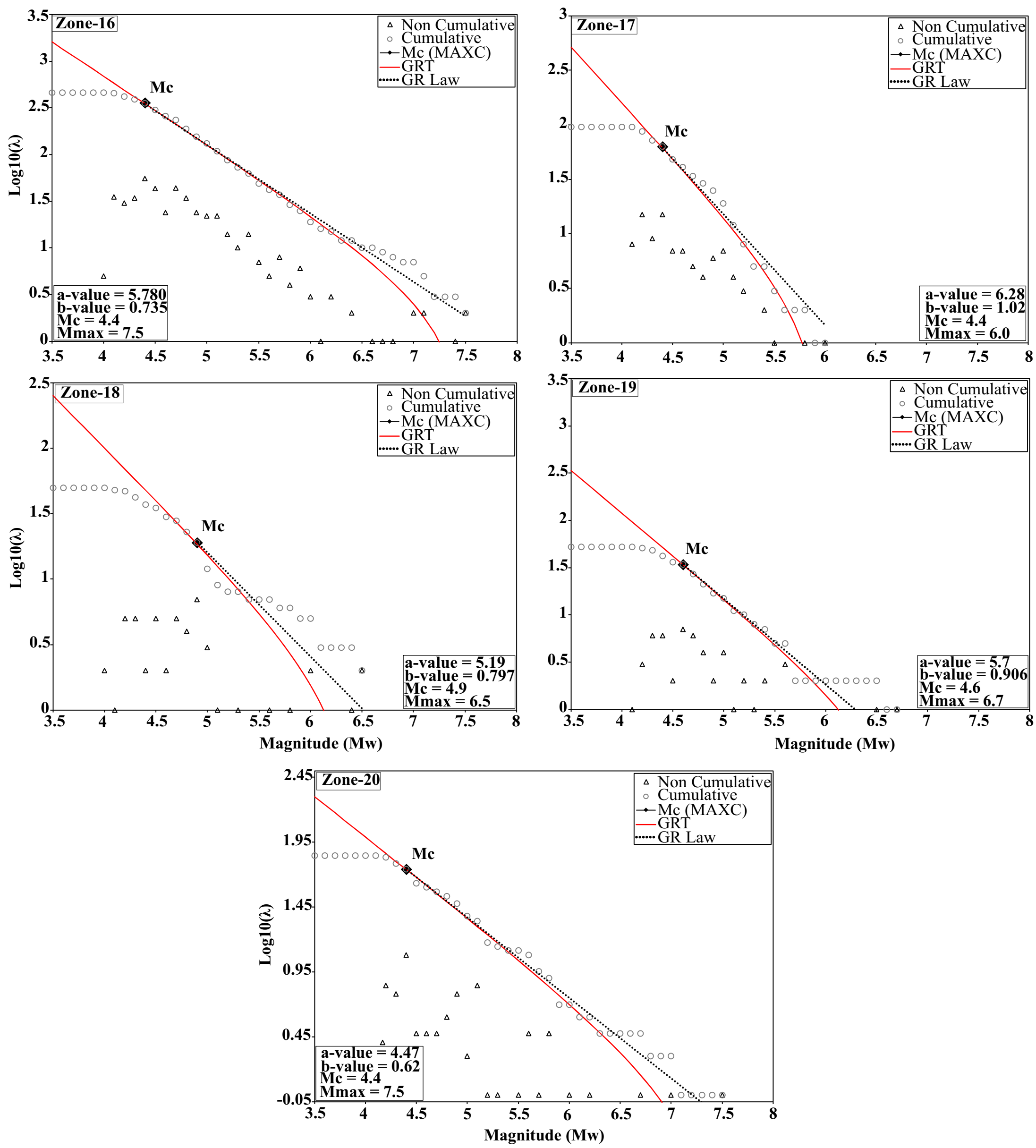


**Fig. 14** Cumulative curve with complete magnitudes for deep seismic sources. Seismicity parameters, i.e. *b* values, are estimated using the maximum likelihood method of Aki (1965). Blank circles represent cumulative data, and triangles show non-cumulative data

*July 1985, Hindu Kush, Afghanistan* The considerable shock ($M_W$ 7.4, depth 99 km) was felt in Afghanistan. Some parts of Tajikistan and neighbouring Pakistan also felt this earthquake. A total life loss of five was noted in Swat and Chitral, Pakistan.

*9 August 1993, Hindu Kush, Afghanistan ($M_W$ 7.0 (NEIC, HRV), 215 km depth)* This event was strongly felt in South and Central Asia, from "Dushanbe, Tajikistan", to as far south as "Multan, Pakistan".

*27 February 1997, near Harnai, Pakistan* This was the strongest earthquake that occurred in Pakistan for several decades with a moment magnitude of 7.3 (NEIC). A total life loss of 50 was documented during this earthquake in the cities of Sibi, Quetta and Harnai.

*26 January 2001, near Bhachau (Gujarat), India ($M_W$ 7.6, depth of 22 km)* This was a great earthquake of magnitude (*M*) 7.6, with an epicentre near Bhachau, India, and was also felt in Bangladesh. The total estimated life loss is 11,500 in Gujarat and 20 in southern Pakistan.

*8 October 2005, Kashmir earthquake* This was a devastating earthquake of magnitude (*M*) 7.6 (NEIC) with an epicentre 19 km northeast of Muzaffarabad that was felt in Pakistan, India, and Afghanistan and is responsible for a great loss of life and damage to buildings.

*28 and 29 October 2008, Ziarat earthquake* The earthquake epicentre is nearly 50 km northeast of the historical 1935 (*M* 7.6) earthquake location and responsible for a total life loss of 30,000 people.

*19 January 2011, Dalbandin earthquake* This earthquake occurred at 01:23 AM local time with a moment magnitude of $M_W$ 7.2 and an MMI of VI (strong). The shock occurred in a sparsely populated area of Baluchistan and caused moderate damage, three deaths and some injuries. This earthquake occurred as a result of normal faulting within the lithosphere of the subducted Arabian Plate.

*16 April 2013, Saravan earthquake ($M_W$ 7.7)* This was a 25-s earthquake that hit in a mountainous area close to the border of Iran and Pakistan.

*24 September 2013, Awaran earthquake* This was a strong earthquake of magnitude 7.7 (VII MMI) that occurred as a result of oblique strike-slip motion in southwestern Pakistan. Approximately 825 people were affected.

*26 October 2015, Hindu Kush earthquake* This is a recent earthquake (*M* 7.5) that was felt in Pakistan, Afghanistan and parts of India. This was a deep earthquake (212.5 km) with an epicentre 45 km north of \`Alaqahdari-ye Kiran wa Munjan, Afghanistan.

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