Parameterization of 18th January 2011 earthquake in Dalbadin Region, Southwest Pakistan

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Abstract An earthquake of magnitude 7.3 Mw occurred on 18th January 2011 in Southwestern Pakistan, Baluchistan province (Dalbadin Region). The area has complex tectonics due to interaction of Indian, Eurasian and Arabian plates. Both thrust and strike slip earthquakes are dominant in this region with minor, localized normal faulting events. This earthquake under consideration (Dalbadin Earthquake) posed constraints in depth and focal parameters due to lack of data for evaluation of parameters from Pakistan, Iran or Afghanistan region. Normal faulting mechanism has been proposed by many researchers for this earthquake.

In the present study the earthquake was relocated using the technique of travel time residuals. Relocated coordinates and depth were utilized to calculate the focal mechanism solution with outcome of a dominant strike slip mechanism, which is contrary to normal faulting. Relocated coordinates and resulting mechanism are more reliable than many reporting agencies as evaluation in this study is augmented by data from local seismic monitoring network of Pakistan. The tectonics in the area is governed by active subduction along the Makran Subduction Zone. This particular earthquake has strike slip mechanism due to breaking of subducting oceanic plate. This earthquake is located where oceanic lithosphere is subducting along with relative movements between Lut and Helmand blocks. Magnitude of this event i.e. Mw = 7.3, re evaluated depth and a previous study of mechanism of earthquake in same region (Shafiq et al., 2011) also supports the strike slip movement.

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1. Introduction

An earthquake of Moment Magnitude Mw = 7.3 originated in Southwestern Pakistan (Balochistan province) on 18th January 2011 famously known as the Dalbadin earthquake. The National Seismic Monitoring Center of Pakistan...
Meteorological Department reported latitude to be 28.78N and longitude 63.88E and depth 100 km for this earthquake (Fig. 1). The epicenter is located in a remote desert area of the country with a very low population density hence no significant damage reports were received. As per the earthquake data catalog of the Pakistan Meteorological Department the area exhibits a very low level of seismicity with only a few reported earthquakes in the past. The largest reported event is of magnitude 5.3 in 1980 with a depth of 23 km. Present earthquake is unique in terms of its magnitude and location and poses constraints in its parameters. The present study is focusing to determine the correct depth and focal mechanism of this event. In order to evolve the correct parameters earthquakes are first relocated and then the modified depth is utilized for calculation of the focal mechanism.

2. Methodology

In the present study the Grid Search Method (GSM) based on an iterative process using travel time residuals is utilized for relocation of the earthquake in southwestern Pakistan. The process was first developed by Geiger (1910, 1912) commonly known as Geiger’s Iterative method. Clifford (1985) made significant enhancements in Geiger’s method to incorporate the nonlinear behavior of travel time as a function of source position and hypocenter location (e.g., Abd el-aal, 2010a,b). Sambridge and Kennett (2001) and Oye and Roth (2003) further enhanced the location algorithm. Lee and Baker (2006) developed the direct location program which was used by Kanamori et al. (2010) for the analysis of the historical 1907 Sumatra earthquake. All these describe the algorithm of computation and technical requirements for the implementation of GSM based on travel time residuals for the present study. Whereas Bai et al. (2006) delineated the significance of seismic network for errors in earthquake locations which is later utilized for assuring the accuracy of results. Focal mechanism is calculated by use of the P wave first motion recording using the algorithm defined by Yagi (2010).

The simple robust method for hypocenter determination in the present study using the iterative process in GSM utilizing travel time residuals is based on the following equation in which the iterative process is based on trail hypocenter (28.78N, 63.88E and depth 100 km) as determined by the data management center of the Pakistan Meteorological Department.

\[(O - C)_j = (t_{ij} - T_{0j}) - T_j = \left(\frac{\partial t_{ij}}{\partial x_j}\right)dx_j + \left(\frac{\partial t_{ij}}{\partial y_j}\right)dy_j + \left(\frac{\partial t_{ij}}{\partial z_j}\right)dz_j + dTo_j + ds_i\]

where \(t_{ij}\) and \(T_{ij}\) are the theoretical arrival times and the calculated travel times of the \(j\)-th event at the \(i\)-th station, respectively. \(ds_i\) is a correction of a station correction at the \(i\)-th station. \(To\) is the origin time. \(O\) is the observed travel time. \(C\) is the calculated travel time. \(dx, dy, dz\) and \(dTo\) are the corrections to the trial hypocenters. Hypocenter convergence is determined by a reduction of the observed and calculated travel times \((O - C)\). The IASP91 velocity model (Kennett and Engdahl, 1991) is used in this study. For P-waves at teleseismic distances, the new tables in IASP91 are about 0.7 s slower than the 1968 P-tables (Herrin 1968) and on average about 1.8–1.9 s faster than the Jeffreys and Bullen (1940) tables. As the times for all phases are derived from the same velocity model, there is complete consistency between the travel times for different phases at different distances and different focal depths. The permanence of the process in Eq. (1) depends upon the availability of data and geographical coverage. Factors like trade off between hypocenter location and station coordinates for low-density seismic network, further augmented by heterogeneous earth structure can hinder the process. Hurukawa and Imoto, 1992 developed the Modified Joint Hypocenter
Determination program (MJHD) to solve this problem of heterogeneous media. For this particular earthquake under consideration only the iterative method with travel time residual was sufficient due to availability of good quality seismic data and good geographic coverage. So MJHD was not adopted for the present study. Further the role of local monitoring network is underscored for the relocation process in this study.

3. Data collection and analysis

For the present study seismic data from PMD and IRIS data centers are utilized. PMD operates a network of ten broadband stations with data communication using satellite technology while eleven short period stations are installed for which data can be obtained manually for desired time. During the analysis of data from local network gaps or breaks in waveform data, high frequency noise and non availability of data from some stations posed serious problems and only five stations from local network were utilized for the present study. The stations include data from five seismic stations (Umerkot, Quetta, Lahore, Muzaffarabad and Islamabad) (Fig. 2). IRIS data management center (IRIS-DMC) provided data from 220 stations (Fig. 2). Out of these 220 stations only 63 stations were selected for the present study based on quality of data.

Seismic Analysis Code (SAC) developed by Lawrence Livermore National Laboratory (LLNL) has been utilized to analyze the seismic data acquired from IRIS and PMD Data centers. Seismogram from each station was analyzed manually to distinguish phase arrivals. In order to incorporate any misjudgments or human errors only one person analyzed all the seismograms. The process is strictly dependent on the availability of good quality seismic data and good geographic coverage (e.g., Abd el-aal, 2010c, 2011, 2012; Abd el-aal and Soliman, 2013).

The analysis was carried out in two steps. At the first step data from IRIS-DMC are analyzed. Due to different delta and geographic coverage data from 63 stations provided clear P wave arrivals. Other stations either lacked data or phase arrival was not clear due to noise. Later in the analysis above mentioned stations of PMD (Fig. 2 blue diamonds) were added to reduce azimuthal gap. PMD stations had a very high noise level and for some stations data were not available having left with only five stations as input for the analysis. All the analyses were performed at both fixed and free depths. In order to obtain the focal Mechanism Solution Fortran program by Yagi (2010) AZMTAK and PMAN are used. These calculate epicentral distances, azimuth and take off angle for computation of lower hemisphere stereographic projection on an equal area net using P wave motion inversion. A total of 58 stations (local and global) were utilized for this study.

4. Results and discussion

At first instance data from only IRIS-DMC stations (Fig. 2) were utilized. Nearest responding stations for the analysis belonged to the Kyrgyz Seismic Telemetry Network (KN) and the Kazakhstan Seismic Network (KZ). IRIS-DMC provided the much needed geographical coverage for the study. Analysis was performed once for fixed depth hypocenter and then for free depth. The RMS values of travel time residuals for fixed depth and free depth analysis are 1.62 and 1.55 respectively. The detailed results of analysis of travel time residual are given in Annex-1 (Table A.1 and Table A.2) in which Table 1 gives the result of relocation of hypocenter at a fixed depth of 30 km.
while Table 2 gives the results of relocation of hypocenter with free depth analysis using IRIS-DMC data.

In the second phase data from local seismic network from the Pakistan Meteorological Department (PMD) were added. Results of the reevaluated parameters after the inclusion of PMD seismic data are given in Annex-I (Table A.3 and Table A.4) with Table A.3 at fixed depth and Table A.4 at free depth. RMS of residuals after the inclusion of PMD data has decreased with values of 1.58 and 1.36 for fixed and free depth analyses respectively. Results of free depth analysis have shown a general decreasing trend in RMS of observed and calculated travel times supporting more reliable results using free depth location. Table 1 summarizes the results of the analysis.

The data of 63 stations have been used in the study for focal mechanism with inconsistent data from just three stations. One station may have a wrong phase marked which can be attributed to human error. Results of the analysis for focal mechanism are presented in Fig. 3 and Table 2.

United States Geological Survey and Global Centroid Moment Tensor (CMT) have both determined a normal faulting process for this earthquake (Fig. 4 left pane). Results of the present study (Fig. 4 Center Pane) show a dominant strike slip fault movement with a minor component of thrusting. There is no evidence of normal faulting as suspected by many researchers. A previous study by Shafiq et al. (2011) in a nearby region also supports the strike slip movement and points to the fact that non-availability of data can lead to falsified results especially in the case of USGS or CMT solution which does not get any data from this region i.e. Pakistan, Afghanistan, Iran and India. These results have been compared in Fig. 5 showing that inclusion of local data has improved the results.

Bai et al. (2006) used the data at the Northern California Seismic Network (NCSN) and defined errors in locations using data of 117 seismic stations. They have defined the mis-location in earthquake parameters as power law beyond a threshold for stable locations, which is strictly dependent on the number of stations and azimuthal gap (Fig. 5). Based on the findings of Bai et al. (2006) the hypocenter was recalculated in the second phase after the addition of data from the local seismic monitoring network in order to enhance the azimuthal coverage and the number of phases available for analysis and the accuracy and consistency were verified.

In order to judge the accuracy of relocation and focal mechanism analysis, relation between residuals, azimuthal coverage and distance of station was analyzed. For this purpose FORTRAN program DISAZ by Yagi (2010) was utilized. Station distribution in terms of azimuth and distance is shown in Fig. 7, which reveals a cluster of low residual stations up to an azimuthal angle of 150 degrees and a uniform distribution of low residual stations at all distances. Even stations with large azimuthal values and large distance show evenhanded residuals with a maximum value of about 4.0 i.e. only four stations in Fig. 6. These results (Fig. 6) are in agreement with the results of Bai et al. (2006) (Fig. 5) who indicated that the azimuth gap should be below 200 degrees for a reliable location with a minimum of 15 stations to be utilized to reduce errors. Results shown in Fig. 6 satisfy the requirements set forth by Bai et al. (2006) for reducing the location error by provision of data well above the threshold requirement. Amalgamation of PMD and IRIS data has further improved the results and yielded a dominant strike slip mechanism.

Rao and Kalpna, 2005 have presented a tectonic model for the subduction zone between the Indian plate and the Burmese Plate. In the convergence zone between Indian and Burmese
plates they have suggested strike slip mechanism for the upper 90 km depth and Reverse faulting mechanism for the lower 90 km depth in the subduction zone (Fig. 7). In the present study relocated depth (41 km) of the Balochistan earthquake and focal mechanism (Strike Slip) are supported by the tectonic model of Rao and Kalpna, (2005).

Fig. 4  Focal mechanism solutions of earthquakes in Southwest Pakistan (Left): Harvard Centroid Moment Tensor Solution (CMT) solution for the 18-01-2011 event. (Center): Solution developed for the present study (Right): Earthquake of Mag 5.6 Dated 25-10-2009 reported after (Shafiq et al., 2011).

Fig. 5  Mislocation dependent on number of stations (upper pane) and azimithal gap (lower pane). Arrows point to threshold of station and azimuth for location error reduction. Source: Bai et al. (2006).

Fig. 6  Distribution of travel time residuals for different azimuthal values and distances.
5. Conclusion

Earthquakes in the complex tectonic zones of Pakistan pose constraints in their parameters and they are augmented by non-availability of seismic data in and around Pakistan. In the case of earthquake under consideration the earthquake has been relocated twice i.e. with IRIS data first and then location is improved by inclusion of local seismic data from PMD.

The following significant results have been obtained in the present study:

- Present event provided with copious phase counts from global and local seismic networks enabling a reliable depth estimate after the amalgamation of PMD and IRIS data. Relocated hypocenter has a depth of 41 km only in comparison to 100 km depth as reported by PMD.

| Sr. No. | Station Code | Tr. Time | O–C | Station Code | Tr. Time | O–C | Station Code | Tr. Time | O–C |
|---------|--------------|----------|-----|--------------|----------|-----|--------------|----------|-----|
| 1       | PBKT         | 420.73   | 0.96| 26           | ARSA     | 465.96| 0.43| 51           | MORW     | 703.68| −0.7 |
| 2       | AML          | 220.02   | 0.93| 27           | QIZ      | 476.65| 0.62| 52           | BLDU     | 711.51| −1.28 |
| 3       | KAR          | 216.97   | 1.12| 28           | KBA      | 475.89| −1.43| 53           | NWAO     | 722.31| −1.12 |
| 4       | UCH          | 223.59   | −1.02| 29           | GRFO     | 489.81| −1.55| 54           | MUN      | 715.54| −0.81 |
| 5       | AAK          | 228.02   | −0.79| 30           | BIT      | 484.73| −1.12| 55           | KMBL     | 732.26| −1.15 |
| 6       | ULHL         | 235.86   | 1    | 31           | DAVA     | 494.05| −2.24| 56           | COEN     | 764.85| 0.09 |
| 7       | KZA          | 228.17   | 0.75| 32           | HIA      | 506.75| −1.18| 57           | PMG      | 771   | 0.8  |
| 8       | GNI          | 268.3    | 4.33| 33           | KEV      | 500.19| −2.25| 58           | HTT      | 795.48| −0.05 |
| 9       | MAZK         | 303.23   | 0.02| 34           | KOM      | 503.48| −1.16| 59           | RABL     | 778.32| −0.67 |
| 10      | MKAR         | 303.56   | −1.02| 35           | KONO     | 513.68| −1.09| 60           | CTAO     | 790.71| −0.06 |
| 11      | LSA          | 313.53   | 2.65| 36           | TATO     | 542.22| 1.89| 61           | BBOO     | 784.29| −0.44 |
| 12      | ZRN          | 317.83   | 0.01| 37           | YOJ      | 551.81| 0.45| 62           | CTA      | 790.69| −0.08 |
| 13      | VOS          | 318.29   | 0.02| 38           | MDJ      | 560.38| 0.85| 63           | QLP      | 798.37| 0.46 |
| 14      | ANTO         | 348.09   | 1.02| 39           | SBM      | 554.1 | 1.26|              |          |      |      |
| 15      | CHTO         | 397.2    | 0.6 | 40           | KBS      | 567.79| −1.41|              |          |      |      |
| 16      | LOEI         | 421.99   | 3.5 | 42           | PAB      | 577.51| −0.24|              |          |      |      |
| 17      | ULN          | 440.37   | 1.62| 43           | ASAJ     | 623.57| −0.58|              |          |      |      |
| 18      | PBKT         | 420.69   | 0.92| 44           | MAJO     | 615.44| −0.41|              |          |      |      |
| 19      | ENH          | 449.93   | 1.32| 45           | YSS      | 619.91| −0.44|              |          |      |      |
| 20      | PANO         | 445.14   | 0.78| 46           | MACI     | 664.17| 0.13|              |          |      |      |
| 21      | KMBO         | 447.43   | 3.91| 47           | GIRL     | 672.35| 1.23|              |          |      |      |
| 22      | IPM          | 474.55   | 1.28| 48           | MBWA     | 687.67| −0.29|              |          |      |      |
| 23      | SKLT         | 450.53   | −7.36| 49           | FITZ     | 702.26| 0.05|              |          |      |      |
| 24      | UBPT         | 457.25   | 0.1 | 50           | MTN      | 707.78| −1.87|              |          |      |      |

Fig. 7 Source mechanisms of earthquakes at the subduction zone of Indo-Burma ranges Rao and Kalpna, 2005.
Parameterization of 18th January 2011 earthquake in Dalbadin Region, Southwest Pakistan

### Table A.2 Parameters after relocation at free depth (calculated depth 75 km).

| Station Code | Tr. Time | O–C | Station Code | Tr. Time | O–C | Station Code | Tr. Time | O–C |
|--------------|----------|-----|--------------|----------|-----|--------------|----------|-----|
| PBKT         | 415.63   | 0.59| ARSA         | 460.86   | 0.41| MORW        | 698.58   | −0.95|
| AML          | 214.92   | −0.08| QIZ          | 471.55   | 0.46| BLDU        | 706.41   | −1.5 |
| KKAR         | 211.87   | 0.17| KBA          | 470.79   | −1.35| NWAO        | 717.21   | −1.3 |
| UCH          | 218.49   | −1.93| GRFO         | 484.71   | −1.37| MUN         | 710.44   | −1.01|
| AAK          | 222.92   | 1.50| JT            | 479.63   | −0.63| KMBL        | 727.16   | −1.25|
| UHL          | 230.76   | 0.26| DAVA          | 488.95   | 2.20| COEN        | 759.75   | 0.39 |
| KZA          | 223.07   | 0.03| HIA           | 501.65   | −0.57| PMG         | 765.9    | 1.15 |
| GNI          | 263.2    | 3.48| KEV           | 495.09   | −1.65| HTT         | 790.38   | 0.05 |
| MAEZ         | 298.13   | 0.34| KOM           | 498.38   | −1.73| RABL        | 773.22   | −0.21|
| MKAR         | 298.46   | −0.76| KONO          | 508.58   | −0.71| CTAO        | 785.61   | 0.22 |
| LSA          | 308.43   | 2.45| TATO          | 537.12   | 2.09| BBDO        | 779.19   | −0.35|
| ZRN          | 312.73   | 0.65| YOJ           | 546.71   | 0.75| CTA         | 785.59   | 0.2  |
| VOS          | 313.19   | 0.65| MDJ           | 555.28   | 1.53| QLP         | 793.27   | 0.66 |
| ANTO         | 343.29   | 0.71| SBM           | 549.00   | 0.97|             |          |     |
| CHTO         | 392.1    | 0.19| KBS           | 562.69   | −0.65|             |          |     |
| PHRA         | 403.23   | 0.66| JOW           | 573.87   | 0.43|             |          |     |
| LOEI         | 416.89   | 3.12| PAB           | 572.41   | −0.18|             |          |     |
| ULN          | 435.27   | 2.13| ASAJ          | 618.47   | 0.18|             |          |     |
| PBKT         | 415.59   | 0.55| MAJO          | 610.34   | 0.27|             |          |     |
| ENH          | 444.83   | 1.43| YSS           | 614.81   | 0.32|             |          |     |
| PANO         | 440.04   | 0.46| MACI          | 659.07   | 0.3 |             |          |     |
| KMBO         | 442.33   | 2.34| GIRL          | 667.25   | 0.87|             |          |     |
| IPM          | 469.45   | 0.62| MBWA          | 682.57   | −0.47|             |          |     |
| SKLT         | 445.43   | 0.46| FITZ          | 697.16   | −0.03|             |          |     |
| UBPT         | 452.15   | −0.18| MTN           | 702.68   | −1.76|             |          |     |

### Table A.3 Parameters after relocation at a fixed depth of 30 km (PMD-IRIS data).

| Station Code | Tr. Time | O–C | Station Code | Tr. Time | O–C | Station Code | Tr. Time | O–C |
|--------------|----------|-----|--------------|----------|-----|--------------|----------|-----|
| UMKT         | 88.79    | −0.66| PANO         | 445.14   | 0.61| MACI        | 664.17   | 0.25|
| QUET         | 49.64    | 1.01| KMO          | 447.43   | 3.99| GIRL        | 672.35   | 1.1 |
| LHR          | 135.26   | −0.83| IPM          | 474.55   | 1.11| MBWA        | 687.67   | −0.4 |
| MUZF         | 142.05   | −0.62| SKLT         | 450.53   | −7.52| FITZ        | 702.26   | −0.6 |
| ISLM         | 125.68   | 1.24| UBPT         | 457.25   | −0.06| MTN         | 707.78   | −1.98|
| PBKT         | 420.73   | 0.78| ARSA         | 465.96   | 0.51| MORW        | 703.68   | −0.8 |
| AML          | 220.02   | 0.83| QIZ          | 476.65   | 0.46| BLDU        | 711.51   | −1.39|
| KKA          | 216.97   | 1.12| KBA          | 475.89   | −1.27| NWAO        | 715.54   | −0.86|
| UCH          | 223.59   | −1.15| GRF0         | 489.81   | 3.19| MUN         | 722.31   | −1.17|
| AAK          | 228.02   | −0.92| JB            | 484.73   | 1.20| KMBL        | 732.26   | −1.21|
| UHL          | 235.86   | 0.88| DAVA          | 494.05   | −2.16| COEN        | 764.85   | −0.01|
| KZA          | 228.17   | 0.63| HIA           | 506.75   | −1.33| PMG         | 771.36   | 0.7  |
| GNI          | 268.3    | 4.55| KEV           | 500.19   | −2.25| HTT         | 795.48   | −0.1 |
| MAZE         | 303.23   | −0.08| KOM           | 503.48   | −1.32| RABL        | 778.32   | −0.76|
| MKAR         | 303.56   | −1.12| KONO          | 513.68   | −1.02| CTAO        | 790.71   | −0.15|
| LSA          | 313.53   | 2.46| TATO          | 542.22   | 1.74| BBOO        | 784.29   | −0.49|
| ZRN          | 317.83   | 0.01| YOJ           | 551.81   | 0.3 | CTA         | 790.69   | −0.17|
| VOS          | 318.29   | 0.02| MDJ           | 560.38   | 0.77| QLP         | 798.37   | 0.42 |
| ANTO         | 348.09   | 1.24| SBM           | 554.1    | 1.11|             |          |     |
| CHTO         | 397.2    | 0.43| KBS           | 567.79   | −1.41|             |          |     |
| PHRA         | 408.39   | 0.89| JOW           | 578.9    | −0.06|             |          |     |
| LOEI         | 421.99   | 3.33| PAB           | 577.51   | −0.17|             |          |     |
| ULN          | 440.37   | 1.46| ASAJ          | 623.57   | −0.71|             |          |     |
| PBKT         | 420.69   | 0.74| MAJO          | 615.44   | −0.47|             |          |     |
| ENH          | 449.93   | 1.15| YSS           | 619.91   | −0.5 |             |          |     |
There is no evidence of normal faulting in the region. Furthermore, normal faulting in the present tectonic framework may not be able to produce such large magnitude earthquakes.

Mechanism of this earthquake is mainly strike slip with a minor component of thrusting and the present solution is more reliable than the USGS or CMT solution.

Data from the local seismic network of PMD need to be enhanced for stations’ noise levels alongside collaboration in data sharing between different agencies.

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Appendix A.

Tables A.1–A.4.

References

Abd el-aal, A.K., 2010a. Modeling of seismic hazard at the north-eastern part of greater Cairo metropolitan area, Egypt. J. Geophys. Eng. 7, 75–90. http://dx.doi.org/10.1088/1742-2132/7/1/007.

Abd el-aal, A.K., 2010b. Ground motion prediction from nearest seismogenic zones in and around Greater Cairo Area, Egypt. Nat. Hazards Earth Syst. Sci. 10, 1495–1511. http://dx.doi.org/10.5194/nhess-10-1495-2010.

Abd el-aal, A.K., 2010c. Eliminating upper harmonic noise in vibroseis data via numerical simulation. Geophys. J. Int. 181, 1499–1509. http://dx.doi.org/10.1111/j.1365-2478.2010.04594.x.

Abd el-aal, A.K., 2011. Harmonic by harmonic removal technique for improving vibroseis data quality. Geophys. Prospect. 2011 (59), 279–294. http://dx.doi.org/10.1111/j.1365-2487.2010.00918.x.

Abd el-aal, A.K., 2012. Very broadband seismic background noise analysis of permanent good vaulted seismic stations. J. Seismol. 17 (2), 223–237. http://dx.doi.org/10.1007/s10950-012-9308-5.

Abd el-aal, A.K., Soliman, M.S., 2013. New seismic noise models obtained using very broadband stations. Pure Appl. Geophys., online first, doi 10.1007/s00024-013-0640-7.

Bai, L., Wu, Zhongliang, Zhang, Tianzhong, Kawasaki1, Ichiro, 2006. The effect of distribution of stations upon location error: statistical tests based on the double-difference earthquake location algorithm and the bootstrap method. Earth Planets Space 58, 29–39.

Thurber, Clifford H., 1985. Nonlinear earthquake location: theory and examples. Bull. Seismol. Soc. Am. 75 (3), 779–790.

Geiger, L., 1910. Herbstümmung bei Erdbeben aus den Ankunfzeiten. K. Gesell. Wiss. Goett. 4, 331–349.

Geiger, L., 1912. Probability method for the determination of earthquake epicenters from the arrival time only. Bull. St. Louis Univ. 8, 60–71.

Table A.4 Parameters after relocation at free depth using PMD-IRIS data (calculated depth 41 km).

| Hypocenter Parameters | Origin time: 20:23:26.2000UTC | Lat: 28.59N Long: 63.82E | RMS = 1.36 |
|------------------------|-------------------------------|-------------------------|------------|
| Sr. No: Station Code   | Tr. Time O–C                  | Sr. No: Station Code    | Tr. Time O–C |
| 1 UMKT 87.49           | –1.19 26                      | 2 PANO 443.84           | 0.74 51     |
| 2 QUET 48.34           | 0.45 27                       | 3 KMBO 446.13           | 3.79 52     |
| 3 LHR 133.96          | –1.34 28                      | 4 IPM 473.25            | 1.26 53     |
| 4 MUZF 140.75         | –1.12 29                      | 5 SKLT 449.23           | –7.39 54    |
| 5 ISLM 124.38         | 0.86 30                       | 6 UBPT 455.95           | 0.07 55     |
| 6 PBKT 419.43         | 0.99 31                       | 7 ARSA 464.66           | 0.41 56     |
| 7 AML 218.72         | 0.39 32                       | 8 QIZ 475.35            | 0.6 57      |
| 8 KKKR 215.67        | 0.7 33                        | 9 KBA 474.59            | –1.45 58    |
| 9 UCH 222.29         | –1.53 34                      | 10 BJT 483.43           | –1.06 60    |
| 10 AAK 226.72        | –1.16 35                      | 11 DAVA 492.75          | –2.24 61    |
| 11 ULHL 234.56       | 0.54 36                       | 12 HIA 505.45           | –1.18 62    |
| 12 KZA 226.87        | 0.38 37                       | 13 KEV 498.89           | –2.26 63    |
| 13 GNI 267           | 0.07 38                       | 14 KOM 502.18           | –1.16 64    |
| 14 MAKZ 301.93       | –0.09 39                      | 15 KONO 512.38          | –1.09 65    |
| 15 MKAR 302.26       | –1.12 40                      | 16 TATO 540.92          | 1.91 66     |
| 16 LSA 312.23        | 2.55 41                       | 17 YOJ 550.51           | 0.47 67     |
| 17 ZRN 316.53        | 0.01 42                       | 18 MDJ 559.08           | 0.95 68     |
| 18 VOS 316.99        | 0.02 43                       | 19 SBY 552.8            | 1.28        |
| 19 ANTO 346.79       | 0.94 44                       | 20 KBS 566.49           | –1.31       |
| 20 CHTO 395.9        | 0.54 45                       | 21 JOW 577.6            | 0.12        |
| 21 PHRA 407.09       | 1 46                          | 22 PAB 576.21           | –0.2        |
| 22 LOEI 420.69       | 3.45 47                       | 23 ASAJ 622.27          | –0.52 Tr. Time = |
| 23 ULN 439.07        | 1.67 48                       | 24 MAO 614.14           | –0.28 O–C = Observed – Calculated Tr. Time |
| 24 PBKT 419.39       | 0.95 49                       | 25 YSS 618.61           | –0.31 Tr. Time = |

Tr. Time = Travel Time
O–C = Observed – Calculated tr.Time

Table A.4 Parameters after relocation at free depth using PMD-IRIS data (calculated depth 41 km).
Parameterization of 18th January 2011 earthquake in Dalbadin Region, Southwest Pakistan

Herrin, E., 1968. Seismological tables for P-phases. Bull. Seism. Soc. Am. 60, 461–489.
Kanamori, H., Rivera, Luis, Lee, William H.K., 2010. Historical seismograms for unraveling a mysterious earthquake: the 1907 Sumatra Earthquake. Geophys. J. Int. http://dx.doi.org/10.1111/j.1365-246X.2010.04731.x.
Hurukawa, N., Imoto, M., 1992. Subducting oceanic crusts of the Philippine sea and pacific plates and weak-zone-normal compression in the Kanto district, Japan. Geophys. J. Int. 109, 639–652.
Jeffreys, H., Bullen, K.E., 1940. Seismological Tables. British Association for the Advancement of Science, London.
Kennett, B.L.N., Engdahl, E.R., 1991. Travel times for global earthquake location and phase identification. Geophys. J. Int. 105 (2), 429–465.
Lee, W.H.K., Baker, L.M., 2006. Development of a direct search software package for locating poorly constrained earthquakes. Seism. Res. Lett. 77, 291–292.
Oye, V., Roth, M., 2003. Automated seismic event location for hydrocarbon reservoirs. Comput. Geosci. 29, 851–863.
Rao, N.P., Kalpna, 2005. Deformation of the subducted Indian lithospheric slab in the Burmese arc. Geophys. Res. Lett. 32, L05301. http://dx.doi.org/10.1029/2004GL022034, 2005.
Sambridge, M., Kennett, B., 2001. Seismic event location: nonlinear inversion using a neighbourhood algorithm. Pure Appl. Geophys. 158, 241–257.
Seismic Analysis Code, 2010. Lawrence Livermore National Labs. Distributed by IRIS. Peter Goldstein, Arthur Snoke and Brian Savage Binaries and source release, June 2010.
Shafiq Ur Rehman, Tahir Azeeem, Abd el-aal A.K., 2011. Relocation of earthquakes. In: Pakistan Using Broadband Stations, Journal of Geophysics special issue on 13th General Scientific Meeting October 2010, National Research of Astronomy and Geophysics, Egypt, pp. 2–17.
Yagi, Y., 2010. Source Mechanism, software lecture notes and exercises: Training Course in Global Seismological Observation 2010. International Institute of Seismology and Earthquake Engineering (ISEE), Tsukuba, Japan.