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Research Article

Awaran, Pakistan, Earthquake of Mw 7.7 in Makran Accretionary Zone, 24 September 2013: Preliminary Seismotectonic Investigations

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Abstract: A large part of Balochistan in southwest Pakistan was devastated by an earthquake of magnitude Mw 7.7 and focal depth of 10 km on 24 September, 2013. Located in the Makran Accretionary Zone, the Awaran Earthquake was followed by a major aftershock of Mw 7.2 that occurred 90 km NNE of Awaran on 28 September, 2013. The earthquake caused widespread destruction in the remote and poorly accessible area, with death toll exceeding 825. An intensity of IIX on MMI scale is assigned to the epicenter of the main shock using the information from the print and electronic media and some field studies. The damage to property and loss of lives occurred due to non-engineered construction of structures within 100 km of the main shock. Fault-plane solutions of both the main event and its largest aftershock, and the distribution of aftershocks suggest that the NNE-SSW-trending left-lateral strike-slip Awaran Fault is currently active. This is also supported by the analysis of more aftershocks fault-plane solutions. The formation of a mud volcano is the probable cause of the emergence of a 200 x 100 m island off the coast of Gawadar a few hours after the main shock. On the one hand, this event has released high seismic energy in NE-SW direction along the Chaman Fault Zone and Makran Subduction Zone, and on the other it has increased the tectonic stresses in the northern and SE directions, which may cause higher seismicity in future.

Keywords: Awaran Earthquake, Makran Accretionary Zone, Awaran Fault, focal mechanism solutions, intensity map, island emergence

1. INTRODUCTION

A devastating earthquake of magnitude Mw 7.7 (according to United Sates Geological Survey (USGS) and Pakistan Meteorological Department (PMD)) took place in the evening (16:29:50 Pakistan Standard Time (PST)) of 24 September 2013 in Balochistan, southwestern Pakistan. Located about 66 km NNE of Awaran this earthquake took the lives of 825 people; several hundred people were injured. The main shock was followed by a major aftershock of Mw 7.2 (PMD) or Mw 6.8 (USGS), which occurred about 90 km NNE of Awaran (Fig. 1, 2) at 12:34:13 PST on 28 September, 2013. This aftershock, along with nine others, increased the death toll by at least 22 people in the epicentral region. The Awaran District was damaged drastically where 80% homes either collapsed or were seriously damaged. Minor damage, including collapse of a few buildings, was reported from Karachi and Hyderabad according to local media reports. The Earthquake was felt in Rawalpindi/Islamabad, Larkana, Lahore, and also in some parts of India, Oman and United Arab Emirates.

The northward subduction of the Arabian Plate beneath the Eurasian Plate and the northward left-lateral motion of the Indian Plate with respect to Eurasian Plate are the main causes of seismicity in the region. The most active tectonic structure within the area is the Chaman Transform Fault Zone (Fig. 1). This paper does not go into the details of regional tectonics; it describes the seismicity and seismotectonics of the area in the vicinity of the

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Awaran earthquake. Fault-plane solutions of the main event, its largest aftershock on 28 September, 2013, and the aftershock distribution suggest that the NNE-SSW-trending left-lateral strike-slip Awaran Fault (AF), first identified by Quadri and Quadri [1] and Kazmi [2], as shown in Fig. 2, is currently active. However, this assumption is based on limited seismicity data; more fault-plane solutions are needed to understand better the active tectonics and related seismicity level in the region.

2. SEISMOTECTONICS

The active tectonic features in the southwestern part of Pakistan are referred to by Kazmi and Rana [3] and Kazmi and Jan [4] as the Makran-Accretionary Zone (MAZ). Shallow crustal depths (15-20 km), oblique-strike-slip movement in its northern parts and deepening inland to about 80 km, are indicated by various authors [2-5]. Regionally speaking, the active tectonics in MAZ is due to northward sliding of Indian plate with respect to Eurasian plate in the east and northward subduction of Arabian plate beneath the Eurasian plate in the west (Fig. 1, 2). The structures formed due to these motions are NS to NE-SW-striking, and are initially accommodated along the Chaman Fault System. The southern parts of this fault system, referred to as the Ghazaband and Ornach-Nal Faults [6], are the most active tectonic features in the area. The MAZ is bound by left-lateral Ornach-Nal Transform Fault in its east, together with Nai Rud, Ras Malan and Aghor Faults which strike in NE-SW direction and join the Ornach Fault. According to Lawrence et al [7], these strike-slip faults, parallel or subparallel to the Ornach-Nal Fault, form a dense network of fractures (Fig. 1, 2). Southward this zone widens and undergoes transition from a transform to a convergence regime and the structures gradually swing from north-south to southwest and then towards west [4].

Several smaller faults, e.g., Hudishi and Awaran Faults, with signs of recent activity manifested as fault scarps in Recent to Sub-Recent alluvial deposits, have been mapped earlier [2, 5, 8]. However, detailed work is required to locate the causative fault of the Awaran Earthquake. Seismically, this part of Pakistan is active, but a small number of damaging earthquakes has been documented in the recent past. The most important of these are the 1945 (M 8.0) subduction-zone earthquake [9] and 1947 (M 7.3) earthquake [10] having offshore epicenters. The 1945 event, which severely damaged coastal towns and caused a vertical displacement of 4.5 m on the shore, generated a tsunami, and produced upheaval of the sea floor in the form of a row of small offshore islands or mud volcanoes as happened with the Awaran Earthquake [10]. The limited instrumental documentation of seismicity since 1970 shows that shallow depth earthquakes with magnitude range of 3-7 M (Fig. 3) have occurred inland.

3. SEISMIC OBSERVATIONS FOR THE 24 SEPTEMBER 2013 EARTHQUAKE

The local seismic observatory (PMD) provided the following source parameters of the main shock:

Date:	24.09.2013
Time:	15:29:50 PST
Magnitude:	M_w 7.7
Epicentral location:	27.09° N, 65.61° E
Focal depth:	10 km

According to the location provided by the PMD, the main event occurred in an area of MAZ characterized by complex tectonic features dominated by several active thrust as well as oblique strike-slip faults (Fig. 2, 3). The dominant of these faults are Ornach-Nal, Awaran and Hudishi, which are left-lateral strike-slip, faults trending NNE. The main shock was followed by a major aftershock (6.8 M_w according to USGS, and 7.2 M_w according to PMD), which occurred 30 km NNE of the main shock (the main shock resulted in the death of 359 people in the epicentral area). PMD data show the occurrence of 6 foreshocks and 10 aftershocks till 28 September, 2013. The distribution of these foreshocks and aftershocks (Fig. 3) shows some cluster along the Ornach-Nal Fault. However, they are mostly located between the Awaran and

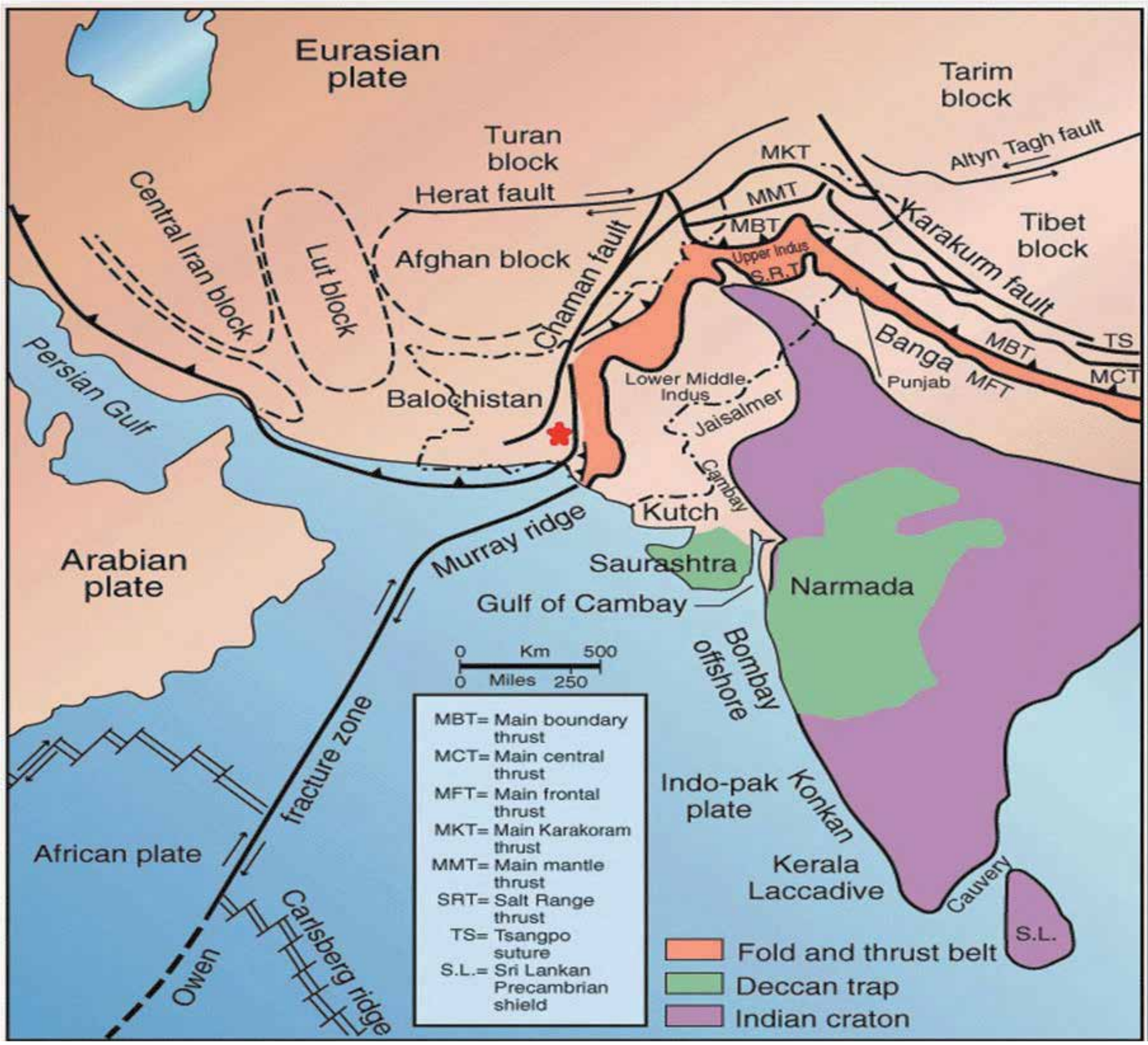
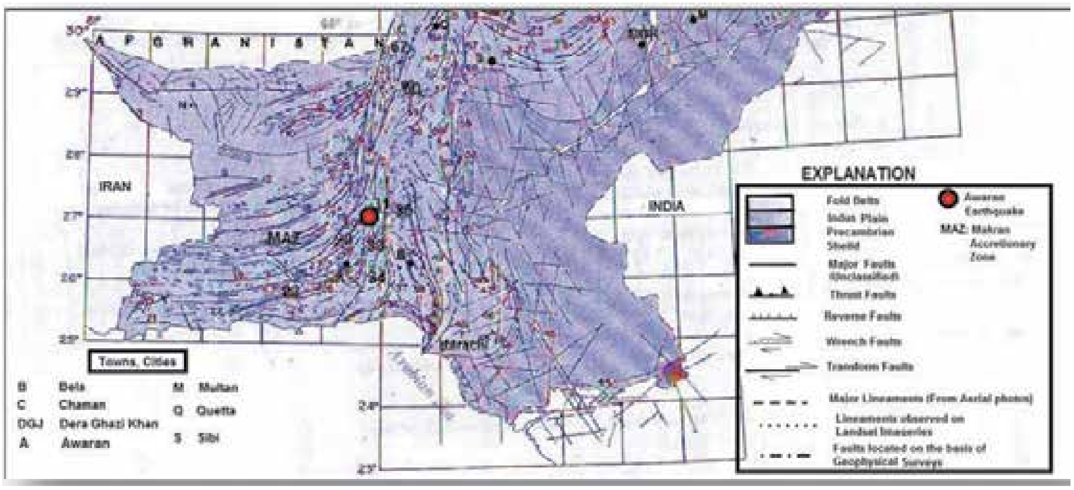


Fig. 1. Tectonic setting of Pakistan and adjacent areas. Location of the 24 September, 2013 Awaran Earthquake and the Chaman Transform Fault are also shown. Modified from Quadri & Quadri [1].

Hudishi faults in a NNE-SSW direction (Fig. 2, 3) suggesting that more than one fault were activated. Most of the foreshocks and aftershocks are at a depth of 10 km. Thus both the aftershocks pattern and depth distribution indicate the activation of shallow surface features, including the Awaran Fault.

4. FOCAL MECHANISM SOLUTIONS (FMS)

The first arrivals of the main event (10 km depth), using the available data of the local as well as international seismic observatories, e.g., PMD, International Seismological Centre and USGS, were used for FMS. The beach ball diagrams were then plotted using the computer programs of AZMTAK and PMAN [11] as shown in Fig. 4. Structurally, this earthquake is surrounded by a number of left-lateral strike-slip faults (Fig. 2). The SSW-NNE-oriented sinistral strike-slip FMS (Table 1) is consistent with the orientation of already existing prominent faults, e.g., the Ornach-Nal Fault, Awaran Fault and Hudishi Fault, along with the major trend of the aftershocks of the main event plotted for the purpose (Fig. 2, 3). Thus, based upon the strike and depth of these faults, the nodal plane striking



ACTIVE FAULTS SHOWN IN THE FIGURE

1. KIRTAKA F.
2. SAINDAK F.
3. WASHAP F.
4. MASHKI CHAH F.
5. DALBANDIN F.
6. AHMADWAL F.
7. BAN F.
8. USMAN F.
9. GARPUK RASKOH F.
10. MUKAK F
11. LADGASHT F.
12. MASHKHEL F.
13. KHARAN F.
14. GARRUK KHARAN F.
15. SIAHAN F.
16. GWANI RIVER F.
17. RAGHAI RUD F.
18. PANJGUR F.
19. HOSHAB F.
20. KULMIR SUNT F.
23. NAI RUD F.
24. GURANGATTI F.
25. JHAL JHAO F.
26. KAPP F.
27. BAZDAR F.
28. PIRANDAR F.
29. AWARAN F.
30. LALANDARI F.
31. HUDISHI F.
32. SISTAG F.
33. RAS MALAN F.
34. AGHOR F.
35. NAL-ORNACH F.
36. SONMIANI F.
37. BELA F.
38. KULRI F.
39. WINDAR F.
40. MOR F.
41. PAB F.
42. HAB F.
43. JHIMPIR F.
44. RANN OF CUTCH
45. TALHAR F.
46. SURJAN F.
47. LAKHNI F.
48. BHIT JANT F.
49. KHUDE F.
50. KIRTHAR F.
51. GAJ F.
52. KARKO F.
53. ZARDAK F.
54. KOTRA F.
55. GANDAVA F.
56. LEHDO F.
57. NANGU F.
58. PANDRAN F.
59. KALAT F.
60. GHAZABAND F.
61. BHALLA DHOR F.
62. CHAMAN F.
63. CHILTAN F.
64. SARIAB-SARAN- TANGI F.
65. JOHAN F.
66. MACH F.
67. MUSHKAF F.
68. BIBAI F.
69. GOGAI F.
70. TAKHATU F .
71. CHINGAN F..
72. MALIK SALAR F.
73. MANA F.
74. ZIARAT F.
75. KHALIFAT F.
76. HARNAI F.
77. TATRA F.
78. TADRI F.
79. BARKHAN F.
80. KOHLU F.
83. KINGRI F.
84. MANIKHAWA F.
85. CHAUDHWAN F.

Fig. 2. Active Faults in south-western Pakistan. The 24 September, 2013 Awaran Earthquake and the Chaman (No. 62), Ghazaband (No. 60), Ornach-Nal (No. 35), Aghor (No. 34), Ras Malan (No. 33), Hudishi (No. 31), Awaran (No. 29), NaiRud (No. 23) faults are also shown. Updated from Kazmi and Rana [3].

Table 1. Focal Mechanism Solution (FMS) parameters of 24 September, 2013 Awaran Earthquake.

FMS No.	Type of FMS	Fault Plane (FP)		Auxiliary Plane (AP)		P-Axis		T-Axis	
		Strike	Dip	Strike	Dip	Strike	Plunge	Strike	Plunge
1	LLSS	231°	70°NE	141°°	90°NW	173°	14°	94°	14°

NE-SW and dipping NW is considered to be the rupture plane (Fig. 4, 5). The location and FMS of this earthquake were consistent with rupture within the Eurasian Plate above the Makran Subduction Zone (Fig. 5); yellow filled circles are showing the locations of epicentres of the Awaran Earthquake and its aftershocks, where the Arabian Plate is subducting beneath the Eurasian Plate [12].

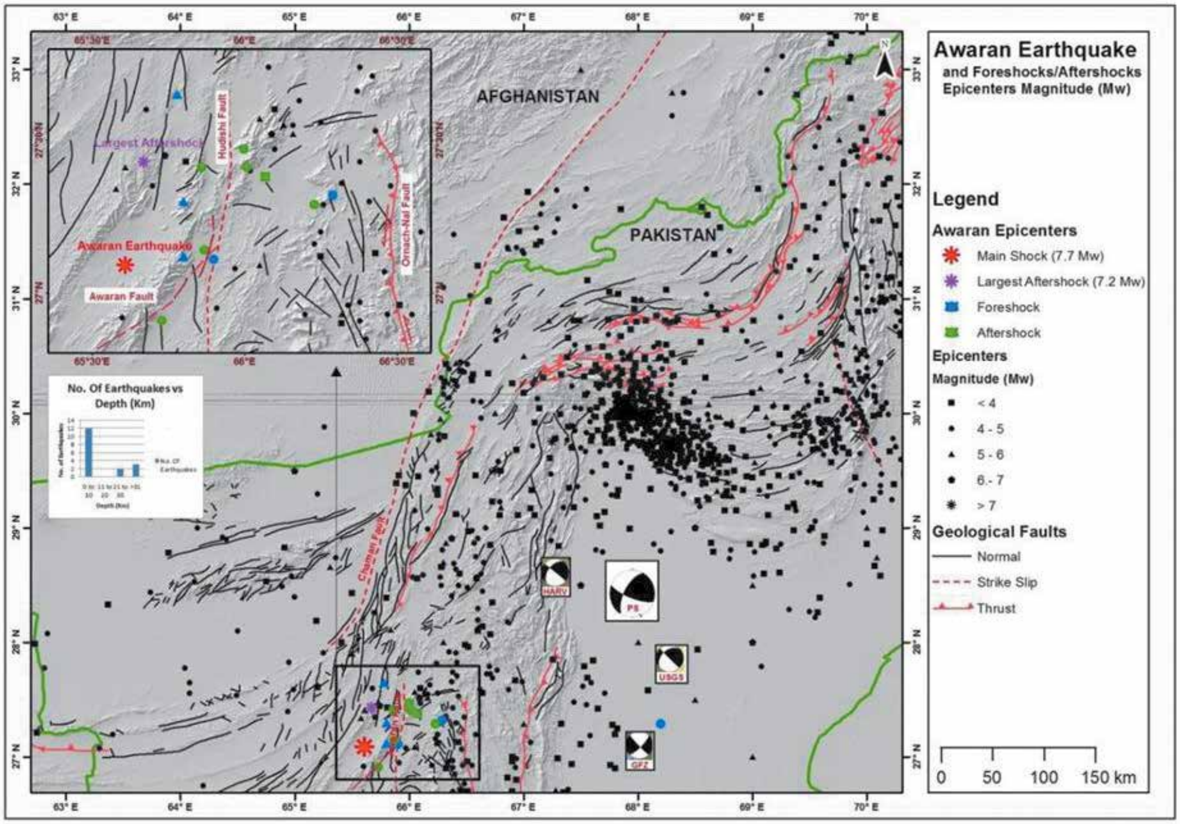


Fig. 3. Map of the study area showing seismicity, active faults, and distribution of foreshocks and aftershocks of the Awaran Earthquake. Focal-mechanism solutions of the main shock from all available sources, i.e., HRV, Harvard, PS, Present Study, USGS, GFZ, Geo Forschungs Zentrum Potsdam, are also shown.

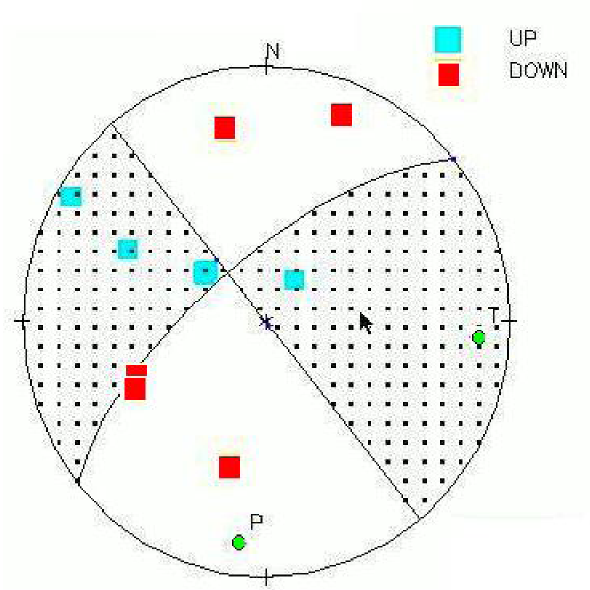


Fig. 4. Focal mechanism solution (FMS) of 24 September, 2013 Awaran Earthquake.

5. INTENSITY AND DAMAGE DISTRIBUTION

The September 24, 2013 Awaran Earthquake was one of the most damaging earthquakes to have occurred in the southwestern part of Pakistan (i.e., Balochistan). Balochistan is the largest but least populous province of Pakistan, with a population of just under eight million. The Balochistan Provincial Disaster Management Authority (PMDA) reported that the main earthquake caused 359 deaths and affected 185,000 people. However, "moderate" to "rather strong" shaking (levels 4 and 5 on the 12-point Mercalli Intensity Scale) were estimated by the USGS across the heavily populated Indus River valley, having a population of some 140 million people. The earthquake was originally rated with a magnitude of Mw 7.4 on the Richter scale, later on upgraded to 7.8, but then revised

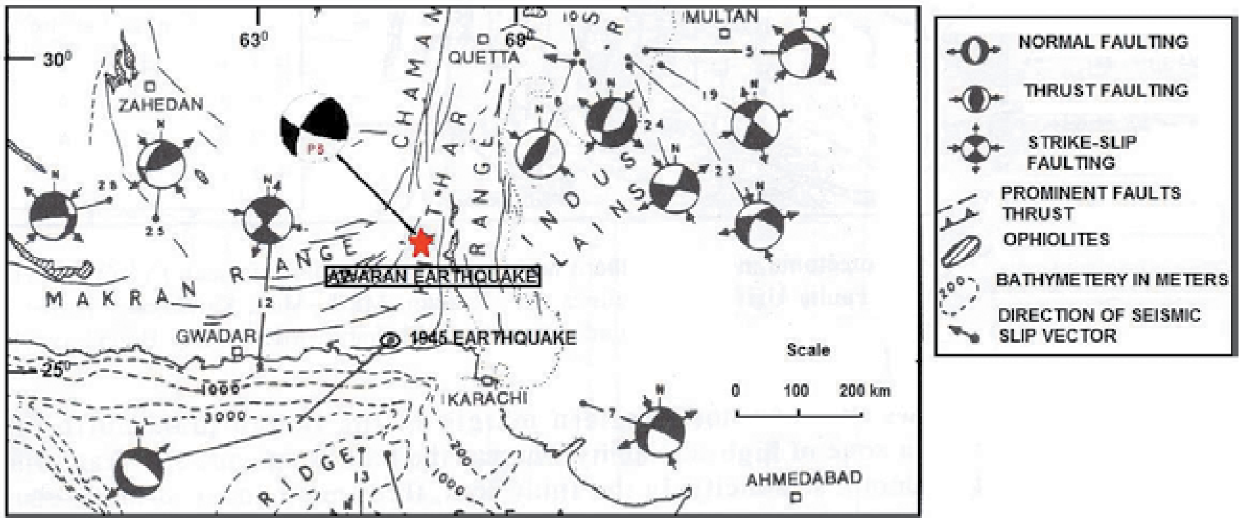


Fig. 5. Map showing the major faults and focal mechanism solutions (FMS) of selected events, including 24 September, 2013 Awaran Earthquake, in the Makran Accretionary Zone and adjacent areas. Dark area in FMS plots shows compression and blank area dilatation [13].

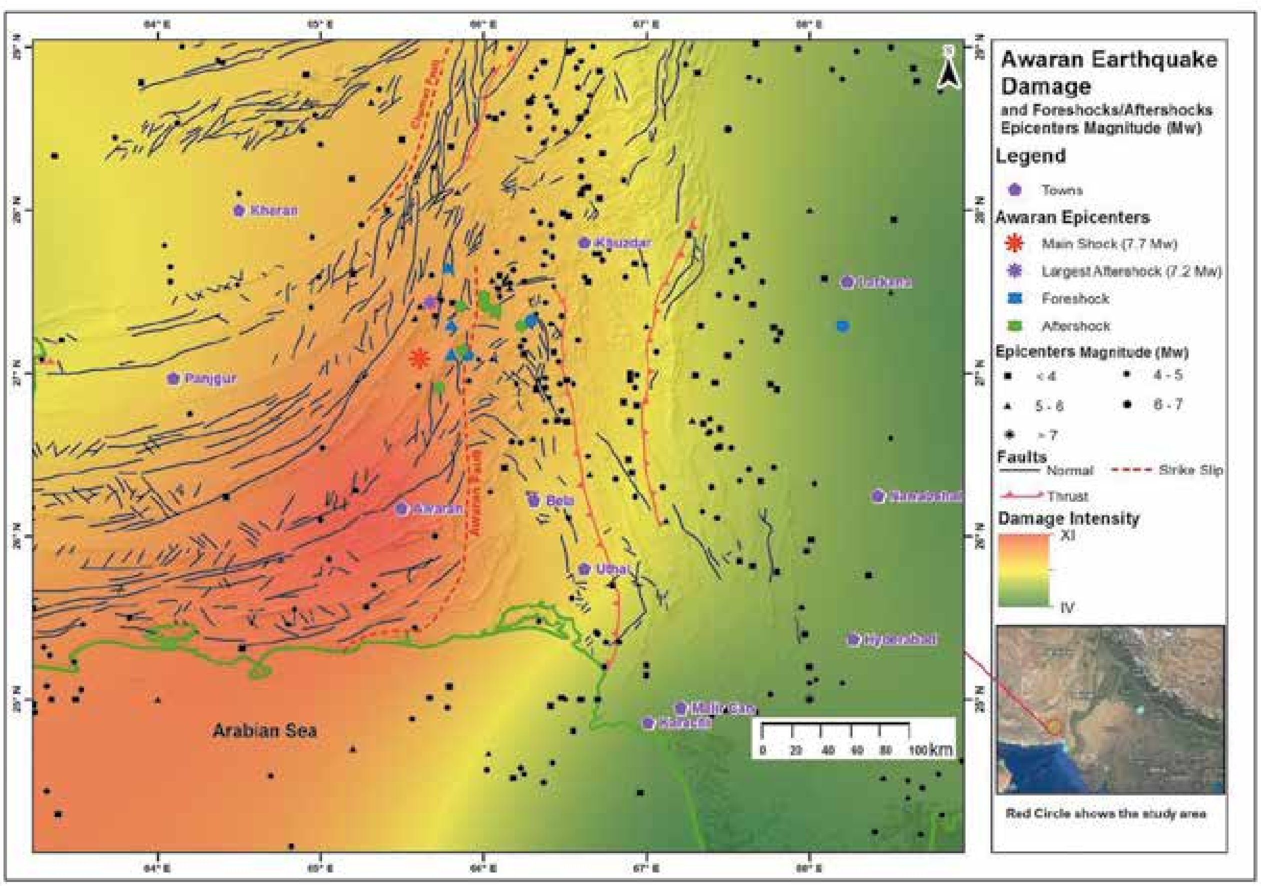


Fig. 6. Intensity map of 24 September, 2013, Awaran Earthquake prepared in the present study.

to 7.7. The destruction caused by this earthquake covered an area of about 100 km radius, but the most severe damage was observed within 30 km of the epicenter. The Awaran Earthquake and its aftershocks, especially its largest aftershock (M_w 7.2 by PMD) of 28 September, 2013 triggered some landslides also which resulted in additional damage. On the basis of information obtained from the print and electronic media, an intensity of MM IIX has been assigned at the epicenter of the main shock.

The intensity map of the Awaran Earthquake, prepared in the current study using the damage/destruction information from the print media and local sources (Fig. 6), shows the intensity within 100 km area of the main shock. One possibility of this heavy damage is the very shallow focal depth of the main shock: 10 km according to PMD. The Awaran District, where > 60,000 people are living within 50 km of the epicenter, is the worst affected area, with over 80 per cent of mud houses reportedly damaged [14]. Majority of the construction in the district is highly vulnerable to earthquake shaking and there are only a few resistant structures. The vulnerable structures are of adobe block and unreinforced brick masonry construction. Other districts affected by the Earthquake include Kech, Gwadar, Panjgur and Khuzdar. The Government of Balochistan, Federal Government, National Disaster Management Authority, and the armed forces of Pakistan provided rescue and immediate relief services (Fig. 7d). Many NGOs have also supported the relief work, providing health care services, shelter, and food items [14], but their efforts were being hampered by the remoteness of the affected areas and insecurity. Some of the damage in Awaran can be seen in the photographs displayed in Fig. 7a–7d.

6. ISLAND EMERGENCE

Close to Pakistan-Iranian political border, an island, about 200 m long and 100 m wide, emerged near Gawadar [1]. Two smaller islands appeared soon after the first island near Ormara town, with diameters of about 10-13 m and a height of <1 m (Fig. 8a, 8b). These islands are mud volcanoes, which are commonly attributed to seismic activity although a number of other factors may also have contributed to their eruption [15]. Balochistan contains over 70 active mud volcanoes [16]. Along with the ten mud volcanoes near the epicentral location of the Awaran main shock, hundreds of meters below the sea floor, MAZ is rich in gas hydrates (sometimes called frozen methane gas, resembling ice). The seabed near the Makran coast has vast deposits of gas hydrates, or frozen gas having large methane content [17]. These hydrates may be explored for commercial purpose, using several safe and cost-efficient technologies available in many countries, including US, Japan, Canada and India. Therefore a survey of the reserves may be carried out immediately. An island emerges within the water or on the sea surface whenever an earthquake occurs in the nearby area. Such islands also accompanied the 1945 Makran (M 8.1) earthquake but were eroded away within a year (as happened in case of AE). These islands emit flammable gas, according to print media.

7. DISCUSSION

The western part of Pakistan and southeastern Afghanistan are experiencing comparatively high velocity left-lateral strike-slip movement along the Chaman Fault. Shallow and destructives earthquakes are commonly related to strike-slip, reverse-slip and oblique-slip faults. In 1505, a segment of the Chaman Fault system near Kabul, Afghanistan ruptured in an earthquake estimated as Ms 7.3, causing widespread destruction in Kabul city and surrounding villages [18]. In the same region, the more recent 17 April, 2013 Mw 7.8 Khash (Iran) Earthquake (near Pakistan-Iran border; 35 deaths), and 28 October, 2008 Mw 6.4 Ziarat Earthquake [19] and 30 May 1935, M7.6 Quetta earthquake (within the Sulaiman Range) killing 300, and 30,000 - 60,000 people, respectively [18], have been significant events. Off the south coast of Pakistan and southeast coast of Iran, the MSZ is the present-day surface expression of active subduction of the

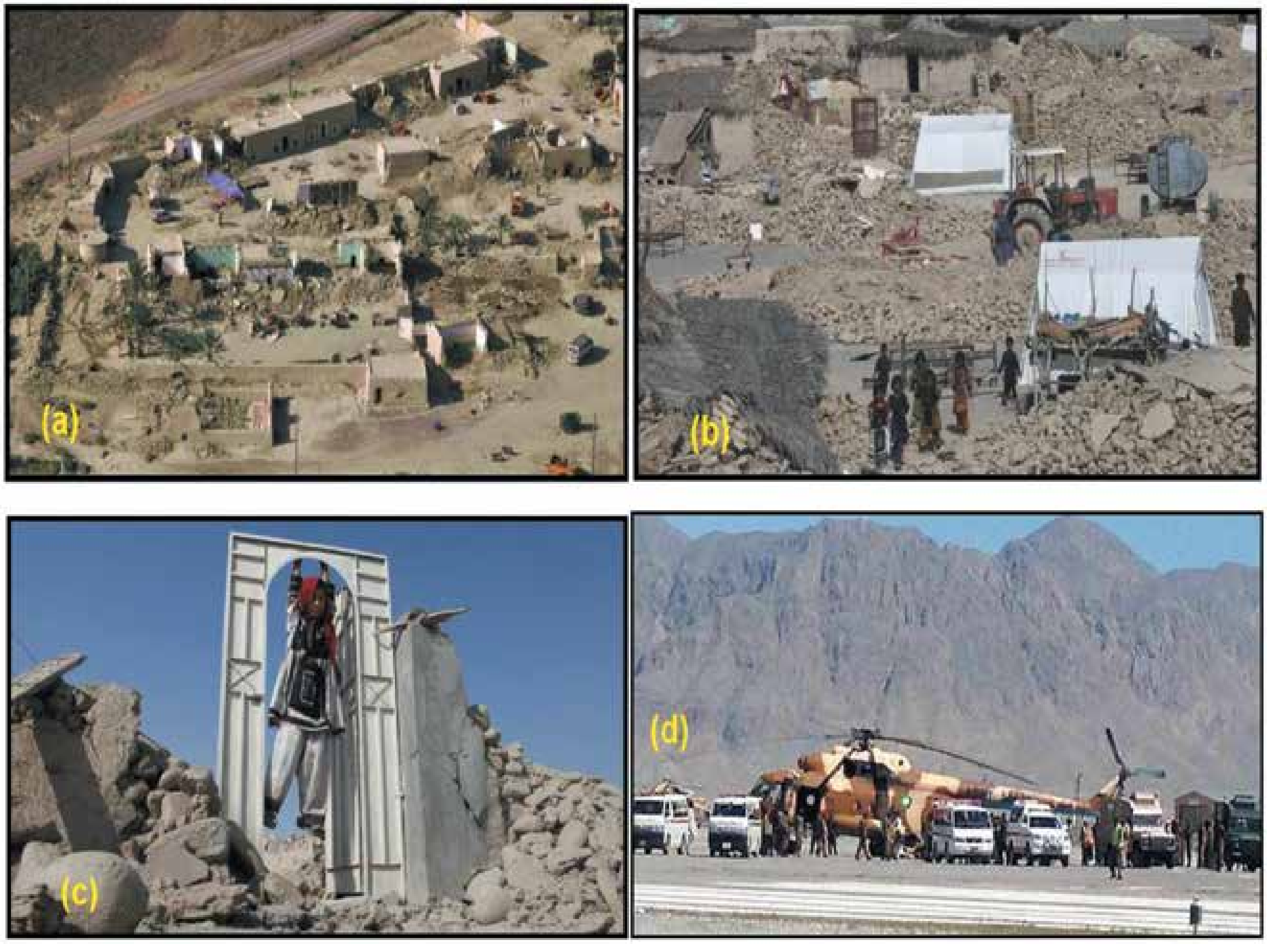


Fig. 7: (a) to (c) Damage and destruction in Awaran, Balochistan; **(d)** Rescue operation by the Pakistan Army.

Fig. 8a and 8b. The Island emerged after 24 September, 2013 Awaran Earthquake (courtesy of NASA and local TV channel). Yellow filled circles in **(a)** represent the location of Awaran Earthquake and its aftershocks, whereas **(b)** shows the offshore island.

oceanic leading edge of the Arabia Plate beneath the continental Eurasia Plate, with a convergence rate of approximately 20 mm/yr [18, 19]. Although the MSZ has a relatively slow convergence rate, it has produced large devastating earthquakes and tsunamis. For example, the November 27, 1945 M 8.1 mega-thrust earthquake produced a tsunami within the Gulf of Oman and Arabia Sea, killing more than 4,000 people. Northwest of this active subduction zone, collision of the Arabia and Eurasia plates forms the approximately 1,500-km long fold and thrust belt of the Zagros Mountains, which crosses the whole of southwestern Iran and extends into northeastern Iraq [20].

Based on this preliminary seismotectonic study of the 24 September, 2013 Awaran Earthquake, it is hypothesized that the MSZ is seismically active, and the Awaran Fault is probably the source of this event. The epicenter of the 1945 earthquake is also located in this region. This 8.1 magnitude earthquake was also of shallow focal depth. We further conclude that the Awaran Fault, which trends NNE-SSW, extends for about 40-50 km from the epicentral location. This is evident by the aftershock pattern, depth distribution and the focal mechanism (Fig. 3, 4, 5). Previous workers, such as [10, 21], have indicated the possibility of a large earthquake in MAZ after 1945 earthquake. A long awaited large earthquake in this area is postulated immediately west of 1945 earthquake site on the basis of recent seismicity pattern. Some parts of this area are also presenting a diffused distribution of earthquakes which cannot be explained at present but can be related with shallow to steeply dipping faults [10]. More detailed integration of the available seismological, geophysical and geological data is required to develop a seismotectonic model for the area.

An intensity of IIX (MMI scale) is observed using the information of damages and destruction from print media (Fig. 6). The damages to construction and loss of lives occurred due to poor construction of structures within 100 km of the main shock (Fig. 7a–7d). Over 80% of Awaran has been completely destroyed, and this damage was escalated by the occurrence of its largest aftershock (M_w 7.2 by PMD) of 28 September, 2013.

The emergence of an off shore island about 200 m long and 100 m wide a few hours after the main shock, is the result of the formation of a mud volcano. Two more, smaller islands appeared soon after the first island. This is basically a combination of mud, sand and water that gushed to the surface after the earthquake. Liquefaction of sand and mud layers may take place after an earthquake, but it takes a strong one to produce an island such as the island off Gawadar [22]. The other possibility can be a rotational landslide, which moves along a rupture surface that is curved or concave (Fig. 8a, 8b). However, more evidence is required to support this assumption. In fact, the causes of the eruption of mud volcanoes, despite their triggering by earthquakes, are yet to be clearly understood [15], Further, the emission of methane gas is not an exception as the energy released by the seismic movement of these faults in MSZ activates inflammable gases in the seabed.

8. CONCLUSIONS

The Awaran Earthquake event has released high seismic energy in NE-SW direction along the Chaman Fault zone and MSZ; however it has increased the tectonic stresses in the northern and SE directions, which may cause high seismicity in future. It is also worth noting that this big event triggered many off shoots and splays of the larger faults (data to be presented separately). Thus, the possibility of large earthquakes, in future, causing serious damage in the cities situated in the area, cannot be excluded. It is, therefore, suggested that an effective National Seismic Hazard Study program should be perused with emphasis on precise delineation of high risk zones.

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