

## Seismotectonic analyses of Karachi Arc, Southern Kirthar Fold Belt, Pakistan

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**Abstract:** In this study geomorphological and seismotectonic analyses were carried out in Karachi arc area, southern Pakistan to locate relatively safe areas from earthquakes disasters. Karachi arc is the southern extremity of the Kirthar mountain chain that occupies a major part of southern Pakistan and is comprised of a number of narrow, elongated mountain ranges, i.e. Laki, Kirthar, Khud, Pab and Mor ranges. Based on geomorphological and seismotectonic analyses Karachi arc area has been divided into three parts. These parts are northern, frontal and southern part. The northern part of Karachi arc is seismically active where minor to moderate (3-5.9Mb) earthquakes occurred. Some basement structures in Sehwan area seem to be still active and affected by the present-day transpressional stress field. The frontal part of Karachi arc is also active as manifested by the existence of active faults in Jhimpir, Surjan and Meting areas. These embryonic structures in the eastern part of the Arc are indicators of active deformation of Karachi arc. Presently the active deformation is taking place in frontal and northern parts of the arc, while the southern part that has experienced deformation prior to Quaternary time is inactive and is relatively stable geoblock. The instrumental and historic seismicity record of the adjoining areas of Karachi arc show that the area has experienced light to moderate seismic events (4-5.9) with occasional occurrence of strong and major earthquakes. Any major or strong event in Katch rift zone, Makran subduction zone and Ornach-Nal fault zone may cause intensity of VII to VIII in Karachi arc area as well as Karachi city of environmental seismic intensity scale 2007.

**Keywords:** Geomorphology, seismotectonic, neotectonic, Karachi arc, Kirthar fold belt.

### Introduction

Seismotectonic is the study of the relationship among earthquakes, seismogenic structures and individual faults in an area. By analyzing the combination of regional structures, recent instrumental and historical seismic events and geomorphological evidence, it attempts to understand which fault is responsible for seismic activity in an area.

Karachi arc is located near the junction of three major crustal plates i.e. the Eurasian plate, the Arabian plate, and the Indian plate (Tahirkheli et al., 1979). In the southwest of the Karachi arc, the Arabian plate is subducting under the Afghan and Lut blocks of Eurasia along the Makran subduction zone (Sarwar and Dejong, 1979; Pervaiz et al., 2002). In the north, the Indus Tsangpo suture is a collision boundary between Eurasia and India, while in the west the two convergent plate boundaries are connected by a sinistral transform fault called Chaman-Ornach-Nal Fault (Lawrence et al., 1981; Niamatullah, 1997; Ul-Hadi et al., 2013; Avouac et al., 2014). Continental collision during the Cenozoic resulted in the development of Himalayas Hindu Kush and the Tibetan plateau in the north while Sulaiman-Kirthar fold belt on its western margin (Banks and Warburton, 1986; Jadoon et al., 1994).

The study area is the southernmost part of the Sulaiman Kirthar Fold Belt (Fig. 1). This fold belt

extends for about 850 km in a north-south direction and represents the deformed western margin of the Indian plate (Sarwar and Dejong, 1979; Schelling, 1999). The belt is further divided into Sulaiman arc, Sibi trough, and Kirthar fold belt (Kazmi and Jan, 1997). The southern part of the Kirthar fold belt represents a divergent wrench regime. It is marked by open arcuate structures collectively called Karachi arc (Schelling, 1999; Sarwar and Alizai, 2013). The Indian plate is drifting toward north with an estimated rate of 45 mm/year (Ahmad Abir et al., 2015). This movement resulted in some devastating earthquakes such as Kashmir earthquake in 2005 (Bilham, 2006). Karachi arc is a part of this active mobile belt and has been reported as seismically active geoblock (Quittmeyer and Jacob, 1979; Bilham et al., 2007; Sarwar and Alizai, 2013).

The geomorphological and seismotectonic studies were carried to improve the knowledge on the seismotectonics of Karachi arc area and to evaluate potential seismic areas through seismotectonic analysis. The present work will provide basis for seismic hazard assessment, and earthquake resistant engineering. This work will help in recognizing earthquake prone areas and quantifying seismic hazard associated with seismogenic structures responsible for seismic activity within the Karachi arc as well as for Karachi city for the safety of public and property.

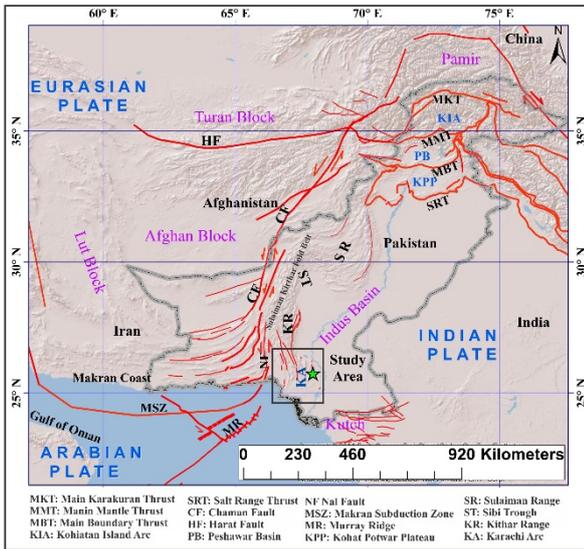


Fig. 1 Tectonic map of Pakistan and surrounding areas showing major structural units. Major faults marked in red (modified after Ul-Hadi et al., 2013; Nabi et al., 2018).

**Regional Tectonics**

Karachi arc belongs to the Kirthar fold belt and represents its southern arcuate portion. The arc is characterized by east-vergent imbricate fan structures and a structural transition zone separated it from the northern Kirthar fold belt characterized by a passive roof duplex structure (Schelling, 1999). Karachi arc is constituted by open arcuate folds and hinterland dipping reverse or oblique-slip faults in the south while in the north the anticlinal folds are relatively tight where crustal shortening is further being accommodated by reverse and oblique-slip faults (Schelling, 1999). It is evident from the structural style (Fig 2), that anticlockwise rotational movement caused convergence in the north which is exhibited by the tight folds and faults while in the southern part of the arc, pre-rotation structures were modified into arcuate folds by divergent wrenching (Kazmi and Rana, 1982). The structure style indicates that the arc moved eastward by thin-skinned tectonic style and the zone of decollement probably lies in the Eocene strata (Sarwar and Dejong, 1979). The eastward transport also has component of counter clockwise rotation due to drag along the western sinistral Ornach-Nal fault. The eastward movement has been focused along the frontal part, where oscillatory movements have repeatedly occurred since early Tertiary, as indicated by unconformities in geological strata (Sarwar and Dejong, 1979). To the east of Karachi arc extensional tectonics were experienced during the rifting period of Indian plate from Madagascar, and the Sindh Monocline is characterized by rifting in late Jurassic to early Cretaceous; followed by modification in Middle Cretaceous, then by inversion in early Eocene (Ahmed et al., 2018).

Numerous catalogs of earthquakes in the Indus delta include an earthquake in A.D. 893 or 894 that is

known from archival sources to have destroyed the town of Debal (old name of Karachi). Yule and Burnell, (1903) suggested that Debal (Karachi) and many other villages in the Indus river delta were relocated several times due to tearing of the Indus river and its tributaries. Lambrick, (1964) also concluded that the old city was abandoned due to unavailability of water not by earthquake. The historical seismicity for the southern Pakistan has been documented by various authors (Banerji, 1957; Bakr and Jackson, 1964; Seeber and Armbruster, 1979). Quittmeyer and Jacob (1979) compiled historical and instrumental seismicity in Pakistan and its surrounding areas and classified seismicity in Pakistan based on the correlation between seismology and active faults, elongated belts similar to faults and diffusive seismicity. Bilham et al. (2007) documented a review of historical seismicity near Karachi and concluded that Karachi is located near the subduction zone with Mw 8 to the west, earthquakes related to reverse faulting with Mw 6-8 in the Kachchh region to the east, strike slip ruptures with Mw 7.9 to the northwest. Sarwar and Alizai, (2013) presented the instrumental seismic data of southern Karachi arc and concluded that the entire Karachi arc is seismically active and extended the southern wrench boundary fault to the south of Karachi arc.

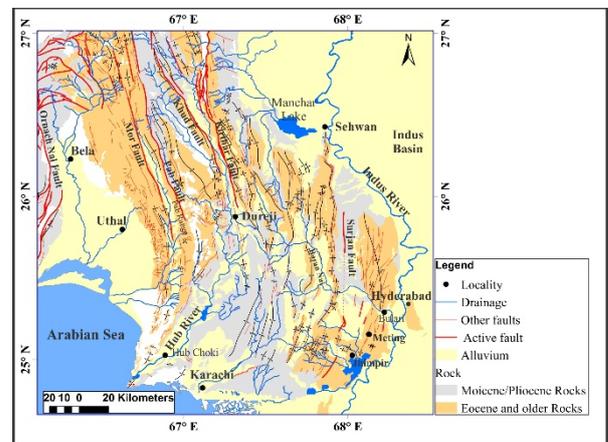


Fig. 2 Geological map of southern Kirthar fold belt and Karachi arc area (after Hunting Survey Corporation, 1961; Schelling, 1999).

The Karachi arc and surrounding areas are comprised of a variety of rocks ranging in age from early Jurassic to Recent (Shah, 2009; Malkani and Zafar, 2016). The early Jurassic to middle Cretaceous rocks are mainly composed of limestone with subordinate shale. The late Cretaceous to Eocene rocks are dominantly limestone with minor calcareous shales. Middle Miocene to Quaternary rocks are composed of sandstone, shale, conglomerate and alluvial sand, silt and clay. The older rock units of Jurassic to Eocene ages are exposed in the west, north and northeast. Quaternary detritus shed by Indus river is lying over Oligocene to Pleistocene sediments in the Arabian sea (Pervaiz et al., 2002). Early Quaternary sediments are represented by alluvial fans, gritty and coarse

sandstone. Recent (Quaternary) alluvium is mainly represented by silt, gravel and occasionally silty/clay.

## Materials and Methods

Geomorphological and seismotectonic studies were carried out, which include analyses and interpretation of landform, slopes, nature of rocks, drainage pattern and characterization of faults and seismicity. The applied methods were based on visual analyses of condensed contour lines, digital elevation models (DEM), LANDSAT and SPOT satellite data interpretation and on numerous direct and reported geological and geomorphological information. Presumable manifestations of recent movements in the current regional topography were identified and assessed.

To provide input for the database, active faults were identified on the bases of DEM, LANDSAT and SPOT satellite images, published geologic maps at different scales, historical and instrumental seismicity and neotectonic signatures inferred from tectonic geomorphology as well satellite image interpretation. Previous research work on geological structures and active faults in southern Pakistan and its vicinity were analyzed and their findings were evaluated and incorporated into the fault trace definition and seismotectonic parameterization. The relationship between the seismicity, tectonic activity and capable structures in Karachi arc area were studied and analyzed. The geomorphological deformations were analyzed in Quaternary strata their correlation with bedrock lithology was studied. The Karachi arc area has been divided into three seismotectonic zones in the present work based upon neotectonics, recent instrumental data, geodynamic information and seismotectonic analyses.

## Results and Discussion

### Geomorphological Units

The area is mainly occupied by Kirthar mountain range that is about 560km long in the north south direction and can broadly be divided into two types of landforms i.e. hilly and alluvial fans. The mountain chain in southern Kirthar range is constituted of about NS trending narrow elongated parallel to sub-parallel ridges separated by relatively broader valleys except Lakhra range in east, which has a broad and gentle positive physiographic expression (Fig. 3). From east to west, major ranges in the Karachi arc include Lakhra, Laki, Badhra, Bhit, Kirthar, Khud, Pab and Mor ranges. These ridges are mostly anticlines however in the southern part, plunging folds also form ridges with flat tops and cliffs at the flanks. The competent rocks exposed in the axial parts constitute broad ridge tops while cliffs have been developed at the limits of synclinal fold by erosion of softer rock units.

The Laki range in frontal part of southern arcuate Kirthar mountain chain is a narrow elongated arcuate ridge with convex side towards east (Fig. 3). Its southern part in Thana Bulla Khan area is called Surjan Range. The mountain front part is marked by a sharp and linear mountain-piedmont junction. However, this linear mountain-piedmont junction is due to folding and the internal small faults in the range. There is no range-bounding fault.

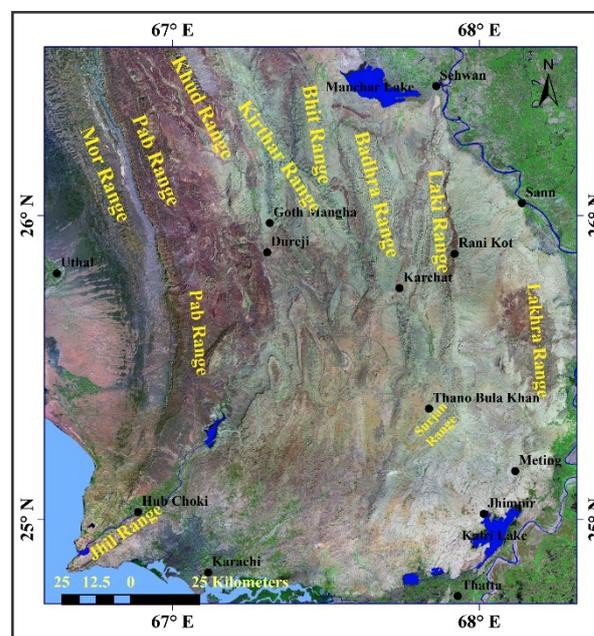


Fig. 3 Landsat ETM satellite image of Karachi arc showing the major geomorphological units.

**Kirthar range:** In the eastern part of the Kirthar fold belt, Eocene strata are riding over Oligocene rocks along the foreland-dipping Kirthar fault (Humayon et al., 1991). The fault is high angle near surface while it gradually flattens toward east (Figs. 3, 4). The Eocene limestone along the fault forms the Kirthar range.

**Khud range:** The NNW oriented Khud Range is located to the west of Kirthar range. The eastern slopes are relatively steeper than the western slopes. The junction of the frontal valley floor and the ridge is not very sharp and straight. Free faces of fault scarp are not well pronounced (Figs. 3, 4). The valley is filled by detritus brought down by streams in the form of prograding fans. Stream channels are entrenched in the proximal part of alluvial fans. These characters suggest low tectonic activity rate along the range bounding fault located at foot of eastern slopes of Khude range.

**Pab Range** is a narrow elongated asymmetric ridge. Satellite image shows that very well developed and exhibited triangular facets mark the steeper eastern slope (Fig. 3). In north, the range bounding fault is marked by a linear break in slope while towards south the straight junction of valley floor and ridge represents the trace of fault.

The Mor range constitutes the westernmost positive signature of the Kirthar mountain chain. The Mor range is again asymmetric with a steeper eastern slope (Fig 3). At places triangular facets are well developed, however the junction of valley and slope is irregular or sinuous indicating that Mor range bounding fault is presently inactive or it has very low rate of activity.

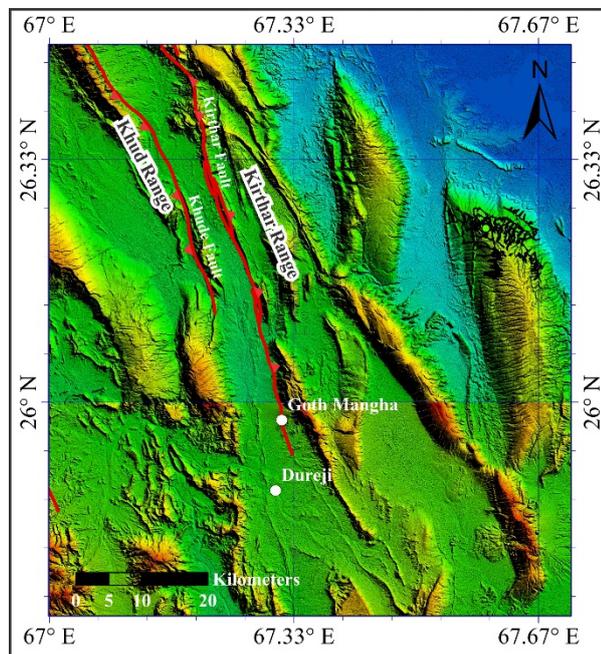


Fig. 4 Digital elevation model of Dureji area showing Kirthar and Khud faults.

### Neotectonics of Karachi Arc

The major faults in northern part of Karachi arc are Kirthar, Pab, Khud and Mor Faults while the frontal part of the arc is characterized by small active faults of limited strike length these faults are Surjan, Bizan Dhoro and few minor faults at Jhampir-Meting area. In Karachi arc area, Kirthar fault is a north-south trending thrust in the frontal part of the Kirthar range, and extending from northern Kirthar range to Dureji in south with variable dip of 65° and 43° toward east respectively (Kazmi and Rana, 1982). South of Dureji, the Kirthar fault movement is compensated by folds, crosscutting strike slip faults and some local faults. Due to prolonged and continued episodic reverse movement along the fault, free face has retreated and was modified by the small-scale antithetic faults (Fig 5). Streams crossing through the fault zone show bends in their courses. The valley at footwall, in west of ridge is broad and exhibits a straight and abrupt junction of valley floor and ridge (Fig 4). These areas probably mark the segmentation of Kirthar fault. These geomorphological features indicate that fault is active with low activity rate. The fault gradually flattens towards east. The DEM and image interpretations reveal that fault does not extend in south of Dureji. Schelling (1999) also

documented that Kirthar fault system dies out at the northern boundary of Karachi arc.

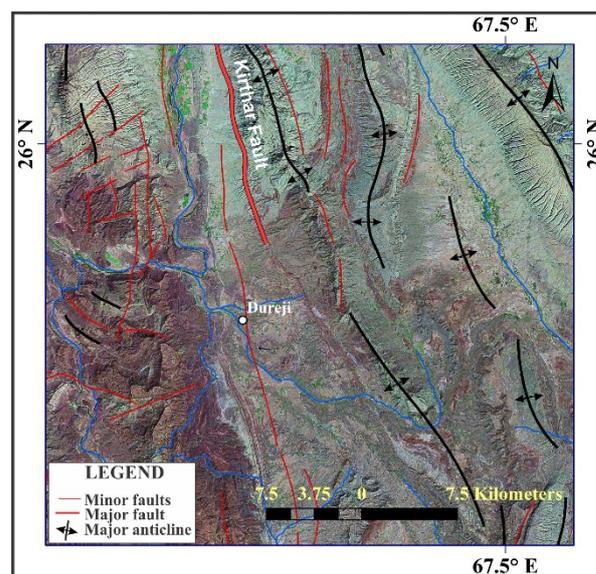


Fig. 5 Landsat ETM satellite image of Karachi arc showing that the Kirthar fault in south of Dureji is compensated by folds and some local faults.

The Khud fault is a NNW trending fault that runs along Khud range. The foreland dipping Kirthar fault and westward dipping Khud fault in front of Khud range constitute a triangular zone that is folded and faulted (Fig 4). The Pab fault in west is another regional, west dipping oblique-slip fault that shows reverse slip with strike-slip component. The fault extends all along the frontal part of Pab range. The fault is segmented in its strike length and fault segments are linked by the strike-slip transfer faults. In south beyond 25.84°N latitude the junction of valley floor and ridge is sinuous and alluvial fan is oriented in NE direction along a strike-slip fault that terminates the Pab range bounding fault (Fig 6). Further, southward the Pab range is bounded by small scale discontinuous faults as exhibited by the arrangement and location of triangular facets. The ridge and valley floor junctions is locally controlled by smaller faults, separated by fold and strike slip shears, while in the south there is no evidence of recent deformation recorded by physiographic expression. These geomorphological features associated with the northern Pab range bounding fault suggest moderate activity rate. Further to the west, the Mor fault lies in front of Mor range. The fault brings Jurassic strata of Mor range over late Mesozoic rocks. The Mor range and its western slopes are highly faulted and fractured by brittle deformation. The Mor fault is segmented and different segments are linked by small faults (Fig. 7).

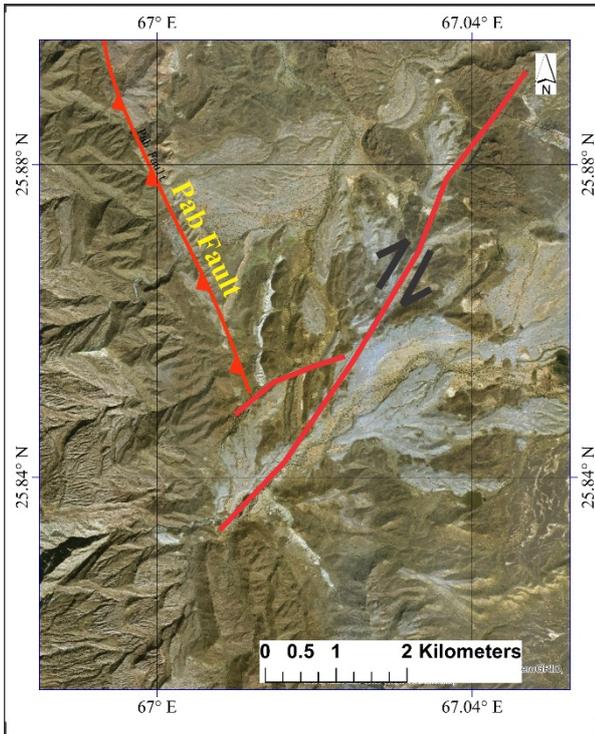


Fig. 6 Alluvial fans are oriented in NE direction along a strike-slip fault that terminates the southern extension of Pab fault.

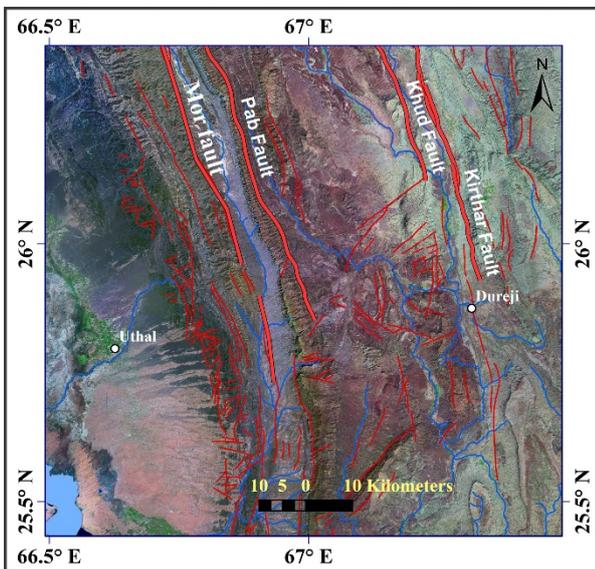


Fig. 7 Interpreted ETM image showing the segmentation of the Mor Fault, different segments are linked by small faults. The image is also depicting highly faulted and fractured old brittle deformation on the western part of Mor range.

The structural trend in frontal Karachi Arc is constituted by open arcuate folds with less frequency and intensity of brittle deformation (Fig 2). The area is characterized by active faulting between Thano Bula Khan and Kalri lake area (Fig 2). Faults in frontal part of Karachi arc are generally local and do not extend more than few kilometers in strike length (3-20km). The NS trending faults of Lakhra anticline near Hyderabad, arcuate reverse faults in Jhimpir area and faults of Laki Range have lengths ranging from 20 to 40km.

### Major Faults Around Karachi Arc

The major seismic zones around Karachi Arc are Murray Ridge (MR), Makran Subduction Zone (MSZ), Ornach-Nal Fault Zone (ONFZ) and Kachchh Rift Zone (KRZ) (Fig 8). The western boundary of Karachi arc is marked by exposures of ophiolitic mélanges, which are thrust over by Mesozoic-Cenozoic shelf strata along a number of NNE or NS trending faults. These faults collectively constitute a segmented fault zone along which disjointed ophiolitic bodies have been emplaced as fault blocks. The wedge shaped Bela-Khuzdar block (Bela trough) is sandwiched between the western extreme of Karachi arc, i.e. Mor range and Ornach-Nal Fault in further west. The Bela trough moved northwards and rotated anticlockwise resulting in the development of the Khuzdar knot in the north and the Bela Trough and Karachi arc in the south (Fig. 8). The Khuzdar knot is comprised of convex northwards, tight arcuate folds and thrusts.

A number of anticlinal structures have been seismically delineated in the offshore which trend NW-SE. Near Murray ridge, the trends of structures change to NS probably due to dragging along plate boundary (Fig. 8). Some of the anticlinal structures are faulted along their eastern limbs (Raza et al., 1990). The Pakistan offshore includes only NW and NE trending faults, whereas EW faults have not been reported even from the offshore indicating that the EW trending fault zone of Kachchh area does not exist in the offshore area of Pakistan.

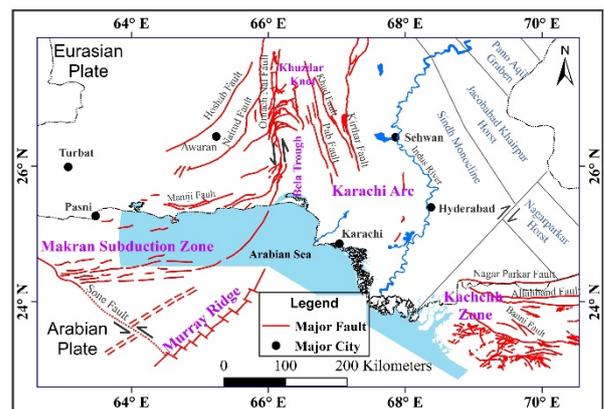


Fig. 8 Major active faults around Karachi arc.

The Makran Subduction Zone (MSZ) is about 900km long E-W trending structure that forms the boundary between Arabian plate and Eurasian plate. Along MSZ the Arabian plate in subduction under Eurasian plate with estimated average rate of 33-40mm/year (Apel et al., 2006; DeMets et al., 2010). The seismicity of the MSZ is comparatively low and the historic record is fragmentary and incomplete. Therefore, the recurrence interval of large tsunamigenic earthquakes (MW>8) is unknown. The only instrumentally recorded tsunami within the MSZ occurred on 28<sup>th</sup> November 1945 (7.5 to 8.3). The earthquakes recorded in this zone are associated with thrust and compression. By

comparison of earthquake environmental effects observed in Karachi city during the event of 1945 event; it can be suggested that any great event in the eastern part of MSZ may cause intensity of VII to VIII in Karachi city.

The distribution and intensity of geopressures (formation pressure) in offshore of Pakistan are predicted through seismic and drilling data. It is indicated that except for the area close to Murray ridge, which is a zone of high geopressure, the rest of the offshore is relatively low pressured. Majority of structures are found in the range of hydrostatic to moderate geopressure (Raza et al., 1990).

A major seismic zone known as Kachchh Rift Zone (KRZ) is located to the southeast of Karachi arc. The zone extends for approximately 250 km in east west direction and 150 km in north south direction. The major active faults of KRZ including from south to north, Kachchh Mainland, Banni Belt, Allah Band and Nagar Parker Faults (Chowksey et al., 2016; Mathew et al., 2006) seem to be converging and mark the western terminus of the Kachchh rift zone. The KRZ experienced many episodes of tectonic movement throughout the Cenozoic times and its western termination is marked by lower rate of activity as compared to central and western parts.

The east west trending faults in the KRZ has been reported to extend in Karachi area (Sarwar and Dejong, 1979). Sarwar and Alizai (2013) extended the southern wrench boundary Kachchh fault to the south of Karachi arc up to Jhil range dextral faults. However, the Jhil range faults have very limited strike length and even do not extend more than few hundred meters through Manchar Formation of Pliocene age in the south of Jhil range (Fig 3). The dextral faults of Jhil Range are part of characteristic strike-slip faulting of Kirthar range caused by transpression and are not extending up to KRZ. Historical and instrumental seismicity also support this idea. The drag of ONFZ, anticlockwise rotation and development of Bela trough and its subsequent northward movement collectively resulted into arcuate structures of Karachi arc. The arcuate structures are obviously marked with strike slip faulting obliquely cutting the regional trends.

**Seismicity**

The NEIC (National Earthquake Information Centre (USGS, 2018)) catalogue record of 383 earthquake events with magnitude >3 was statistically analyzed and plotted on the map (Fig 9). These events occurred between 1940 to October 2018 in the surrounding of Karachi arc area. The epicenters are plotted by arranging the data in five classes of magnitude while focal depth of each event is mentioned in Fig 10. The magnitudes of the earthquakes located in regional area mainly range from 3 to 5.9 with 98.4% of all the events occurred in the study area shown (Fig. 9). Only

1.6% events are greater than magnitude of six. Two events of magnitude 7.7 were recorded in this area (Fig. 9). The maximum recorded magnitude and its aftershocks are located in north of Awaran and Kachchh area. The focal depth of events in surrounding areas of Karachi arc ranges from 3.5 km to 205 km. The shallowest events that originated from shallow depths mostly occurred in MSZ, ONFZ and KRZ.

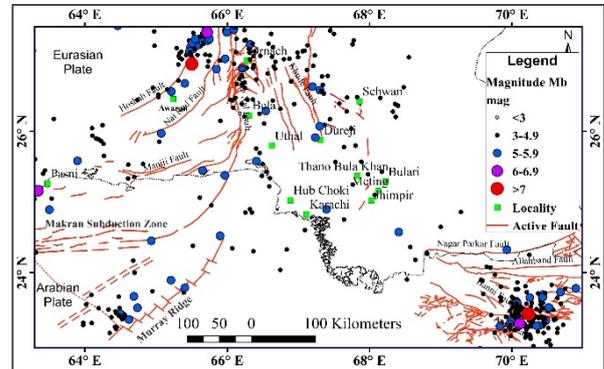


Fig. 9 Distribution of earthquakes magnitude around Karachi arc. (structure map modified after Ul-Hadi et al., 2013; Nabi et al., 2018; seismicity source, USGS).

Szeliga et al. (2012) concluded that velocity through Ornach-Nal Fault is about 15mm/year and the locking depth may be less than 3 km. The ONFZ that extends northwards more or less along longitude 66° E, marks the boundary between Indian and Asian plates. The difference in dynamics and deformation style across the ONFZ is also manifested by the seismic behavior. The seismic data plotted on figure 10 reveals that MSZ is marked with shallow zone of deformation as compared to Kirthar fold belt in west. The probability of shallow disastrous events is higher in MSZ as compared to the Indian plate.

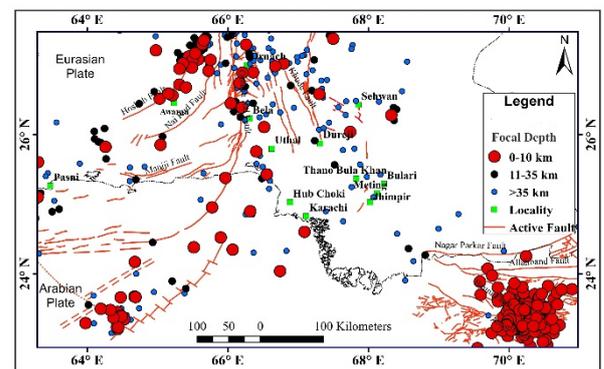


Figure 10: Distribution of earthquake focal depths around Karachi Arc. (seismicity source, USGS, 2018).

The highest frequency of occurrence of earthquakes is exhibited by central KRZ. Most of the events are light to moderate. However, the KRZ has also experienced large earthquakes (Rao et al., 2013; Telesca et al., 2015). The frequency of seismic events is higher in central part of the KRZ while the events are few in its western part (Fig. 9). The seismic events are shallow and represent compressional tectonics (Fig. 10). The faults of KRZ including Nagar Parkar Fault, Allah

Band Fault and Main Land Fault do not extend into Karachi arc, as the arc is a separate tectonic element. A dextral strike-slip fault of the foreland separates the fold belt from the KRZ and the Indus plain located to east of Karachi arc is generally marked with low frequency of seismic events.

To analyze the seismicity of Karachi arc in more detail the seismic data of international seismological center is also analyzed and plotted on map (Fig 11). In total 72 earthquake epicenters of magnitude ranging from 3.0 to 5.7 are located within the Karachi arc area (International Seismological Center). Out of which 26 events are 4 (minor) while 42 events ranged in magnitude from 4 to 5 (light) (Fig 11). Only four events are of moderate intensity (5-5.9) that are located in northwestern part of the arc. The deepest minor seismic event recorded in the area had 118 km focal depth while the shallowest one had focal depth of 9 km. Majority of events were generated at focal depth of 33 km. Three events were generated at focal depths of 53 km, 43 km, and 40 km respectively. One minor seismic event has no record of focal depth.

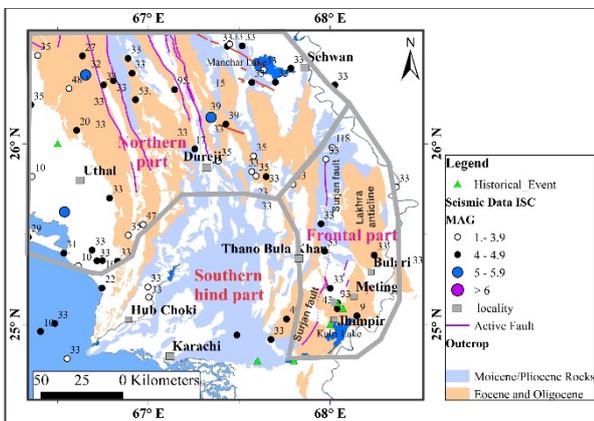


Fig. 11 Seismotectonic zones and major active faults in Karachi arc, the focal depth of each earthquake is represented by numbers while size and colour of the dots show the intensity (seismicity source; international seismological centre, UK)

The seismicity is sparsely distributed in the area. The lower frequency of seismic events reveals that the study area is characterized by minor and light seismic events. The northwestern part of the Arc is characterized by light to moderate seismic events and which may be associated with Kirthar and Pab faults. The moderate seismicity and the absence of strong events reveal that northwestern part of the arc is seismically active with moderate rate and intensity. The seismic intensity in the southwestern inner part of the arc is very low or negligible that is depicting the tectonic stability of the inner hind part of the Karachi arc, the inference is further supported by the absence of capable faults (Pervaiz et al., 2002). Shallow seismic events recorded in Jhimpir area in frontal part of the arc reveal the active deformation in sedimentary cover. These shallow seismic events and presence of Quaternary faults are

indicators of active deformation of Karachi arc in its frontal parts.

The record of seismicity of the adjoining area shows that the area is marked with light to moderate seismic events with occasional occurrence of strong and major earthquakes. The application of ESI 2007 intensity scale to the earthquake environmental effects (EEE) observed during strong and major earthquakes in the adjoining area of Karachi arc, will allow an objective comparison among earthquakes over a geologic time (Table 1). By comparison the EEEs with ESI-2007 scale it is suggested that any major event in the western parts of the KRZ, eastern MSZ and ONFZ may cause intensity of VII to VIII in Karachi arc area.

Table 1 Range of primary and secondary EEEs against intensity in ESI-2007 scale (Michetti et al., 2007).

Intensity	Primacy Effects		Secondary Effects
	Surface rupture length	Surface displacement	Total area
IV	-	-	-
V	-	-	-
VI	-	-	≤ 5km
VII	-	-	10km <sup>2</sup>
VIII	<1Km	<5cm	100km <sup>2</sup>
IX	1-10Km	5-40cm	1,000km <sup>2</sup>
X	10-60km	40-300cm	5,000km <sup>2</sup>
XI	60-150Km	300-700cm	10,000km <sup>2</sup>
XII	>150Km	>700cm	>50,000km <sup>2</sup>

The frontal part of Karachi arc is constituted by open arcuate folds and both hinterland and foreland dipping reverse or oblique-slip faults. In the north, the anticlinal folds are relatively tight, where shortening is further being accommodated by reverse and oblique-slip faults along the eastern limbs or axial parts of the anticlinal folds. The structural style depicts that anticlockwise rotational movement of Indian plate caused convergence in the north, which is displayed by the tight folds and faults while the southern part of the arc shows divergent wrenching. This divergent wrenching modified the pre-rotation structures into arcuate folds (Fig 2). Therefore, southern Karachi arc extends far eastwards in arcuate trend as compared to the northern part.

The faults bounding Mor and Pab ranges are hinterland-dipping thrusts while Kirthar fault and associated thrusts in frontal part of the range are dipping towards foreland. The geometry represents a folded triangular zone. These foreland-dipping faults do not extend southwards beyond Dureji area and further southward the major faults are hinterland dipping (Fig 7). This difference in deformation style discriminate the Karachi Arc from central and northern Kirthar range, hence the active slip along Kirthar fault, Mor fault and Pab fault has no bearing on Karachi Arc in terms of ground rupture, However the adjoining areas has experienced light to moderate seismic events (4-5.9) with occasional occurrence of strong and major earthquakes. Any major or strong event in the KRZ,

MSZ and ONFZ may cause intensity of VII to VIII at Karachi Arc area as well as Karachi city.

The Karachi Arc can be divided into three parts based upon instrumental / historical seismicity, tectonic deformation, capable faults and activity rate (Fig 11). These are the northern, the frontal and the southern hind part. The boundaries of subdivision are obviously loose. The northern part of Karachi arc is seismically active where micro to moderate earthquakes have occurred. The focal depths of all the events are more than 30 km that suggest that the events are of crustal scale. The morphology of basement and thickness of sedimentary cover greatly influence the deformation style in thrust and fold belts. It is evident from the sedimentary record and structural set-up that some Mesozoic basement structure controlled the Tertiary sedimentation and Pleistocene deformation. Some basement structures in Sehwan area seems to be still active and modified by the present-day transpressional stress field. Probably the same structure controlled the termination of Karachi Arc. The geomorphological signature of the area suggests that slip rate is low and slip is accommodated by the cover sediments in the form of fold growth and shearing.

The frontal part of the arc is also active. NS trending faults breach the Lakhra anticline in frontal Karachi Arc and the recent uplift of the anticline is evident from the geomorphic signature, progradation and dispersion of alluvial fans. Shallow seismic event recorded in Jhimpir area in frontal part of the Arc also reveals the active deformation in sedimentary cover. These shallow seismic events and presence of Quaternary faulting in Jhimpir, Meting, Surjan areas and incipient structures depicted in the form of lineaments are indicators of active deformation of Karachi arc in its frontal parts.

Open arcuate folds occupy the southern hind part of Karachi arc, where intensity and frequency of brittle deformation is low as compared to frontal and northern parts of the arc. The hinterland dipping local reverse faults and strike slip faults with limited extent are inactive. The inference is supported by absence of any historical event and behavior of instrumental seismicity. Some minor to light event with more than 30 km focal depth are sparsely distributed in the area. It suggests that events originated from lower part of crust with interaction of crust and mantle. Such events cannot be related with any structure of thrust-fold belt. The inner and hind part of Karachi Arc is not active presently and the deformation has progressed towards east in frontal part of Karachi Arc where shallow seismic events coexist with crustal scale events.

## Conclusion

- The Karachi Arc can be divided into three parts based upon instrumental / historical seismicity, tectonic deformation, active faults and

geomorphology that are northern part, frontal part and inner western part.

- The northern and frontal parts of Karachi Arc are seismically active with micro to moderate (3-5.9) seismic events. The inner hind part that has experienced deformation prior to Quaternary period is inactive and relatively stable geoblock.
- The record of seismicity of the adjoining areas of Karachi arc shows that the area has experienced light to moderate (4-5.9) seismic events with occasional occurrence of strong and major earthquakes. Any major or strong event in the western parts of the Katch region, Makran Subduction Zone and Ornach-Nal Fault Zone may cause intensity of VII to VIII in Karachi arc area (ESI-2007) as well as Karachi city.

Further paleoseismological studies and revisions of the present data are required to determine the tectonic activity rate and earthquake process.

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