Seismotectonics and seismogenic source zones of the Arabian Platform

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Abdullah M. Al-Amri

Introduction

While the Arabian Platform is relatively quite seismically, it is adjacent to a zone of major earthquake activity. Arabian Gulf cities are situated near the eastern margin of the Arabian plate about 300 km from the collision zone between the Arabian and Eurasian plates. The Zagros fold belt (Iran) in the collision zone is a major source of large earthquakes: magnitude 5 earthquakes in the Zagros mountains are frequent, magnitude 6 earthquakes occur several times yearly, and magnitude 7 events occur every decade. It is an open question whether these large events can occur close enough to the eastern region to pose a hazard. These earthquakes may represent the classic low probability, high consequence risk for the population, buildings, and infrastructure of these cities. Moreover, the mechanism of these events is not understood: are they in some way related to the production of hydrocarbons or are they due to tectonic processes arising from the Arabian-Eurasian collision? If due to a tectonic process, are larger, potentially damaging earthquakes possible?

Therefore, this paper suggests an integrated program of seismicity and seismotectonics to address these questions of seismic sources. We will delineate and model seismoginic source zones as a key to assess seismic hazards and model procedure producing maps that engineers and policy makers can use to design an appropriate response to seismic hazards. A better understanding of the seismic hazards and risks is needed, particularly in the area of oil investment constructions over the Arabian Platform.

In the statistical characterization scheme for the seismogenic source zones of the Arabian Platform, different set of seismic data corresponding to two period of observation were utilized. The set of observation period were: 112–1964 AD and 1965–2010. The first set is labeled as historical data while the second set is instrumental data for purposes of discussion. The source catalogues from which the utilized seismic data are taken were the United States Geological Survey (USGS) PDE/EDR: 1963–2010; the International Seismological Center (ISC): 1963–2010: Ambraseys 1988 from 112–1963 AD; the European Mediterranean Seismological Center (EMSC): 1990–2010; the Seismic Studies Center (SSC) of King Saud University from 1986 to 2011, and the Kuwait National Seismological Network (KNSN) from 1997 to 2009. The seismic data obtained from these different seismic bulletins were merged and compiled to provide the main database for delineation and identification of the different seismogenic source zones in eastern Arabian peninsula and for statistical analysis. The compiled seismic data were likewise utilized in the seismotectonic correlation of the activity in each source area. Different types of magnitude such as surface-wave (Ms), body-wave (Mb), local (Ml), duration (Md), macro (Io), and others were converted to two types which are the surface-wave and body-wave to homogenize the main database. The purpose of homogenizing the database is due to the appropriateness of using the Ms in the concept of seismic moment, while the Mb for the seismicity parameters.

In the delineation and identification of the seismogenic source zones in eastern Arabian peninsula, some criteria were followed and utilized as guidelines. These are:

1. Seismological parameter—map of the space–time distribution of seismic events that could indicates the seismogenic provinces and seismoactive faults, and occurrence of large earthquakes, the level of which depends upon the seismic activity in the region.
2. Geological parameter—map of regional tectonics in the area which indicates the location of joints, faults, lineaments, and rift systems that are associated with seismic activities.

A. M. Al-Amri (✉)
Department of Geology and Geophysics, King Saud University, Riyadh, Saudi Arabia
e-mail: amsamri@ksu.edu.sa

K. Al Hosani et al. (eds.), *Lithosphere Dynamics and Sedimentary Basins: The Arabian Plate and Analogues*, Frontiers in Earth Sciences,
DOI: 10.1007/978-3-642-30609-9_15,

The boundaries of the seismogenic source zones are the results in the inter-agreement of these two criteria with the higher priority given to the spatial distribution of epicenters due to statistical needs in statistical analysis. The seismogenic source zones are selected that are composed of systems of faults or lineaments or rift systems whose boundaries do not traverse generally other tectonic units. Some of the seismogenic source zones are relatively large due to scarcity of earthquakes in this part of the eastern Arabian peninsula. From these considerations, there are twelve (15.12) seismogenic source zones that were identified and delineated. These are:

Seismogenic source zone	Source zone
14	Sirhan-Turayf-Widyan Basins
15	Najd Fault Zone
16	Central Arabian Graben Zone
17	Arabian Gulf
18	Zagros Fold Zone
19	Sanadaj-Sirjan Ranges
20	Eastern Yemen
21	Rub Al Khali-Ghudun Basins
22	Dibba-Bandar Abas Region
23	Hawasina-Makran Thrust Region
24	East Sheba Ridge
25	Masirah fault system

The characterization of the seismogenic source zones of the Arabian Platform is also composed of two parts that are similar to the scheme of composition of the western section. These are the brief discussions covering the possible association of each source zone to the tectonic and seismicity in each source area. There are two tectonic sources assumed in each source zone. These are the fault and area sources whose seismic activities are combined to determine the seismicity level using the frequency-magnitude relation. Under the fault source, all types of faults whenever possible are included. Area source is defined to be dislocations found to be off the fault source. The other part is a logic tree diagram for graphical description of the physical and seismicity parameters involved in seismotectonic correlation.

Seismotectonics Setting

Regional Tectonics

The accretionary evolution of the Arabian plate is thought to have originated and formed by amalgation of five Precambrian terranes. These are the Asir; Hijaz, and Midyan terranes from the western part of the Arabian shield, and from the eastern side of the shield are the Afif terrane and the Amar arc of the Ar Rayn micro-plate. The western fusion is along the Bir Umq and Yanbu sutures (Loosveld et al. 1996). The eastern accretion may have started by about 680–640 million years ago (Ma) when the Afif terrane collided with the western shield along the Nabitah suture. At about 670 Ma, a subduction complex formed west of Amar arc (Fig. 15.1). Along this subduction zone, the Afif terrane and Ar Rayn microplate collided that lasted from about 640–620 Ma. The north trending Rayn anticlines and conjugate northwest and northeast fractures and faults may have formed at this time (Al-Husseini 2000).

The regularly spaced north trending Summan platform, Khurais-Burgan and En Nala-Ghawar anticlines, and Qatar arch in the eastern part of the Arabian plate appear to have formed during the Precambrian Amar Collision about 640–620 million years ago (Ma). This collision occurred along the north trending Amar suture that bisects the Arabian peninsula at about 45 degrees east longitude when the Rayn microplate in the east was fused to the western part of the Arabian craton (Al-Husseini 2000; Looseveld et al. 1996; Ziegler 2001). The great anticlines are bounded by the northeast trending Wadi Batin fault and northwest trending Abu Jifan fault that converge on the Amar suture. The anticlines intersected deformed metasediments that are dated as syn-collisional. The Amar collision was followed by a widespread extensional collapse of the Arabian-Nubian shield between about 620–530 Ma. The extensional collapse culminated in the regional development of the extensive Najd fault and its complimentary rift basins, Zagros suture, the northeast trending Oman salt basins, Dibba fault, and the Sinai triple junction. The Sinai triple junction is composed of the Najd fault system, the Egypt rift, the Jordan valley, and Derik rift (Stern and Hedge 1985; Bender 1982; Andrews 1991). During the final extensional stage about 530–570 Ma, the northwest trending Najd fault system dislocated the Arabian shield left-laterally by about 250–300 km. This dislocation appears to compliment the northeast oriented intra-continental rifts in Oman, Zagros Mountain, and the Arabian gulf. These rift basins accumulated thick sequences of clastic and carbonate rocks and salt such as the Ara group in Oman, Hormuz series in the Arabian gulf and Zagros mountain (Ziegler 2001). During the extensional collapse, the north trending anticlines probably remained elevated as elongated horst bounded by normal faults. The intervening subsiding grabens accumulated syn-rift sediments including the Hormuz salt, and form an inter-fingering pattern between the great north trending anti-clines. The striking geometric pattern appears to have formed in two tectonic stages. The Precambtian Amar collision between about 640–620 Ma, followed by the development of the Najd rift system between about 570–530 Ma.

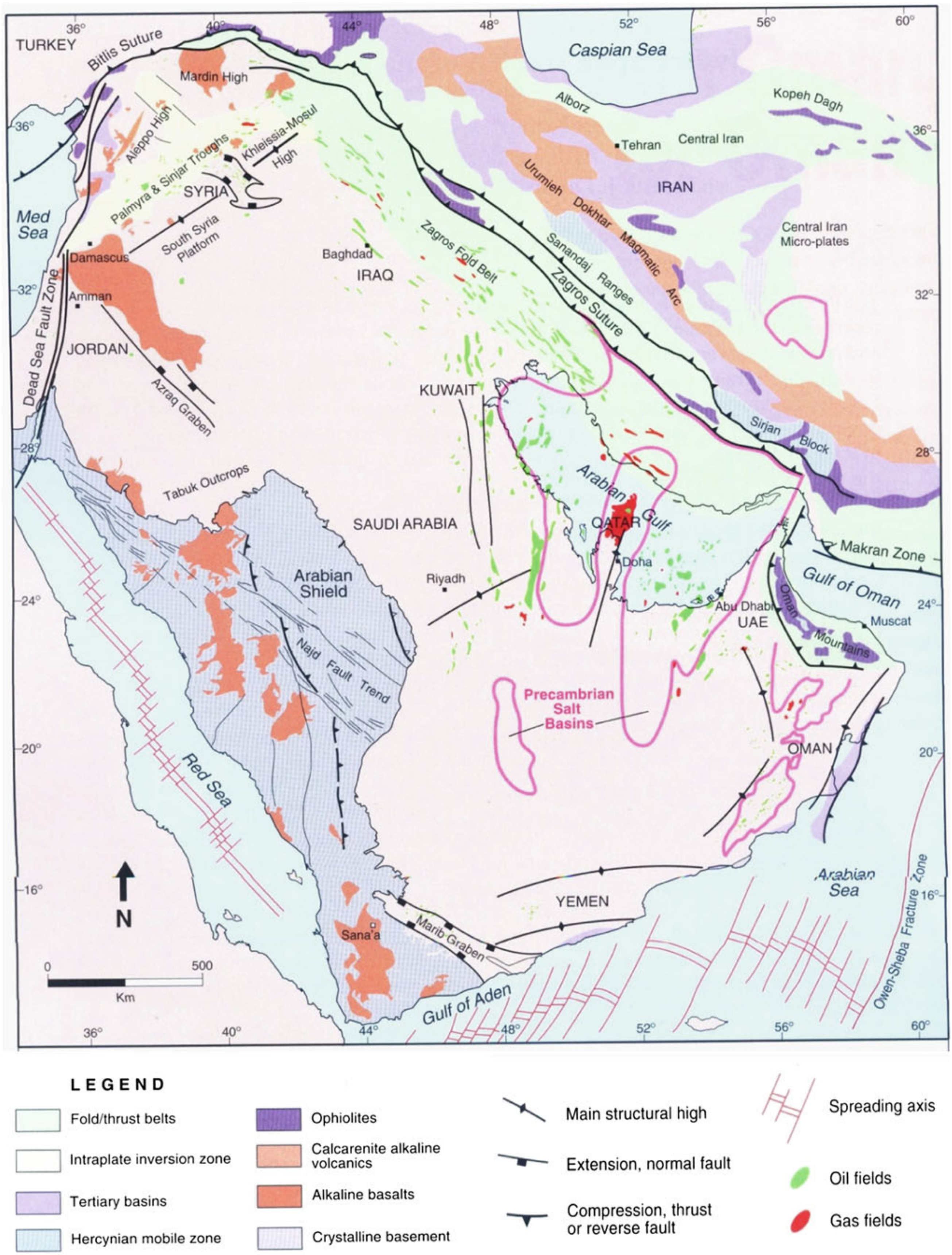


Fig. 15.1 Location map of the Arabian Plate showing major tectonic elements of the Arabian Shield and Platform (Al-Husseini 2000)

In Oman, during the intra-extensional tectonics (Rift Cycle 1), a series of north–south to northeast–southwest trending basement highs may have developed from north to south. These are the Ghudun-Khasfah high, the Anzaus-Rudhwan Ridge and the Makarem-Mabrouk high, separating different basin segments. The event is also associated with igneous activity which is the formation of the Oman mountains and is followed by a thermal subsidence phase. During this cycle, there may have been widespread rifting of the Abu Mahara group (During the Cambrian to mid-Carboniferous (Rift Cycle 2), the Abu Mahara rift configuration was reactivated. The re-activated eastern angle low-angle bounding fault of the Ghudun-Khasfah high becomes the western margin of the asymmetrical South Oman basin. In the north, the Ghaba salt basin develops as a narrower, deeper and asymmetrical feature with some asymmetry reversals. The South Oman and Ghaba salt basins are related to the Najd event of rifting and wrenching dated at between 600 and 540 Ma (Looseveld et al. 1996; Blood 2001).

Around 110 Ma, the Atlantic Ocean started to open, leading to the closure of the Neo-Tethys between the Afro-Arabian and Eurasian plates. A northeasterly dipping intra-oceanic subduction zone developed, accompanied by back-arc spreading. At approximately 93 Ma, this subduction complex collided with the continental crust of Oman. Uplift and partial erosion of the Natih formation and the development of a major hard ground signaled the onset of this event. The initial onset has been described as a mobile or stationary (Robertson 1987; Nolan et al. 1990) fore-bulge that proceeded down-warping of the foreland ahead of the advancing thrust front. During this phase, the Hawasina and Samail Nappes are emplaced, the region south of the nappes are downwarped with local footwall uplift, the Aruma fore deep develops, a dextral trans tension along the Fahud fault zone, and a sinistral trans tension along the Maradi fault zone occur. In the Eocene-Pliocene second Alpine phase, folding commences in the Oman Mountains and shortening overprints extension in the area around Natih, Fahud, and the northern Maradi fault zone (Noweir and Alsharhan 2000). The Salakh arch develops, reverse faulting occur in foredeep, the northern portion of the Maradi fault zone is inverted in dextral transpression, and the Fahud main fault is re-activated with a small sinistral component. At the Cretaceous-Tertiary boundary, intra-oceanic north-over-south thrusting between the lower and upper nappes of Masirah island occurred, immediately followed in the Paleocene by the oblique obduction of the Masirah complex onto the Arabian continent. Along the east coast of Oman, largely offshore under Masirah bay and Sawqrah bay, a narrow, gently folded foreland basin, the Masirah trough, developed. The western margin is bounded by normal faults reactivating Mesozoic rift related faults. On its eastern margin, a wedge of ophiolitic and probably continental slope sediments is largely underthrusted below the eastern and uplifted part of this foredeep basin.

Regional Seismicity

The seismicity map of the Arabian Platform for the period from 1980 to 2010 for magnitude 3 and above is shown in Fig. 15.2 which indicates a sparse distribution of seismic events in the Arabian Platform and western portion of the Arabian Craton. At the central portion of the Arabian shelf, three earthquake events are shown to be positioned among the great anticlines (Summan platform, Khurais-Burgan and Ghawar-En Nala anticlines, Qatar arch) that are bounded by the Wadi Batin and Abu Jifan faults. In the Arabian gulf from the Hormuz salt basin up to the Mesopotamian foredeep of southern Iraq shows also sparse distribution of epicenters, Southeastward of the Arabian shield and south of the central part of the Arabian shelf, three seismic event have epicenters in the Rub Al-Khali basin and two more in the Hadramaut arches in eastern Yemen.

In Oman, two seismic events are located in the Hawasina thrust sheet, while the others are along the Dibba fault and the Makran-Zagros subduction zone. This subduction zone is the only region where an oceanic lithosphere is being subducted, where apparently the oceanic crust in the gulf of Oman is being consumed beneath southern Iran. To the southeast of Oman, along the Masirah trough zone gives one earthquake event. Down south, a spatial concentration of seismic events can be seen. This distribution is in the East Sheba ridge which is between the Alulak-Fartak trench in eastern Yemen to the west and the Owen fracture zone to the east. The ridge is also between the Socotra island in the south and the Masirah trough in the north. The ridge is part of a line of epicenters that connects the gulf of Aden to the west and the Carlsberge ridge to the south.

However, there is an increasing concentration of earthquake epicenters going toward the northeast directions of the Arabian platform and the zone of convergence below the southwestern direction of Lut block in Iran and parallel to the Oman line. One of the concentrated spatial distribution of seismic events is shown to occur in the Zagros Mountains folded belt that extends for a distance of about 1,500 km in a northwest-southeast direction. The simple folded belt is an area of about 250 km in width. The earthquakes in the Zagros folded belt define a zone of about 200 km wide that runs parallel to the fold belt. The majority of earthquakes occur in the crustal part of the Arabian plate that is subducted along the folded belt. Magnitude 5 earthquakes are frequent and magnitude 6 may occur sometimes yearly. This tendency of increasing seismicity thins out in the Main Zagros Thrust (MZT) and the Sanandaj-Sirjan ranges in Iran.

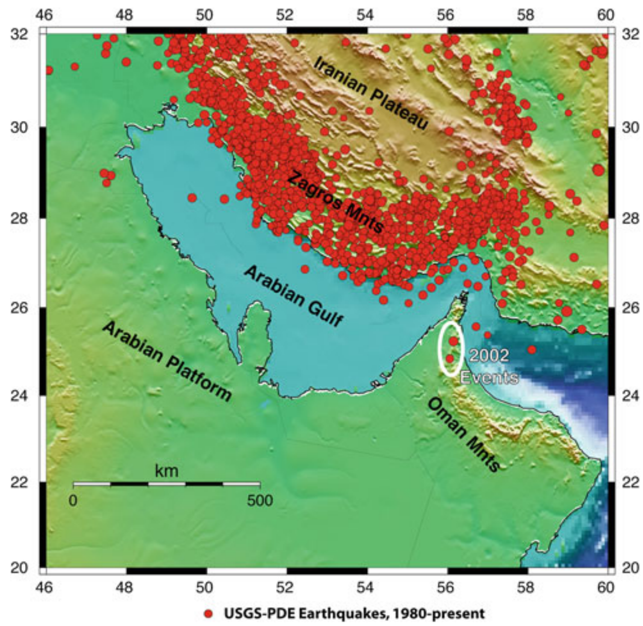


Fig. 15.2 Seismicity of the Arabian Platform and adjacent regions for the period 1980–2010

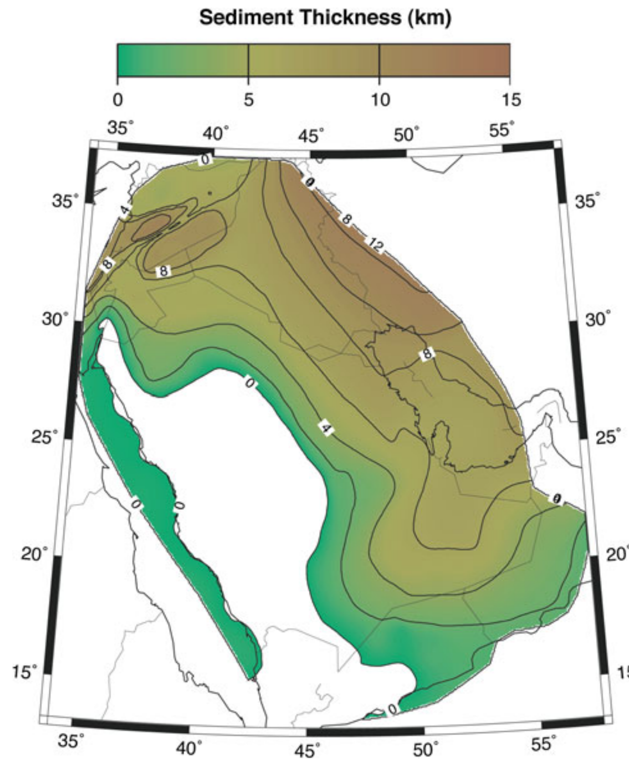


Fig. 15.3 Map of sediment thickness of the Arabian Plate

The crustal model of the western Arabian Platform shows a little higher P-velocity for the upper crust in the Shield than in the Platform and the crustal Platform seems to have a greater thickness than in the Shield by about 3 km (Fig. 15.3). The Moho discontinuity beneath the western Arabian Platform indicates a velocity of 8.2 km/sec of the upper mantle and 42 km depth (Al-Amri 1998, 1999). The sedimentary sequence covering most of the Arabian platform has an average thickness of 5 km and its shear velocity is 2.31 km/s. Its thickness increases towards the east under the interior platform and basins, where it is 7 km on average and consists of two layers-an upper 3 km with a shear velocity of 2 km/s and a lower 4 km with a shear velocity of 3.24 km/s. Seismic velocities within the Gulf sediment structure are very low. Basin structure "traps" and "amplifies" seismic waves. Near-surface (<50 m) velocities most strongly control ground motions amplitudes. Gulf Sedimentary Structure results in long duration high amplitude surface waves. Figure 15.4 indicates two different paths from NHSF station (Iran) and HASS station (Saudi Arabia) for Qeshm island earthquake 27 Nov 2005). Showing how long period ground motion recordings differ from each path.

The Zagros fold and thrust belt forms the boundary between the Arabian and Eurasian plates. Zagros belt is most active seismogenic zones and extend a distance of over 1,500 km in NW–SE direction. The Zagros belt zone is about 200 km wide and most seismic activities take place in the coastal part of the Arabian Plate that underlies the Zagros Folded Belt. It forms the boundary between the Arabian and Eurasian plates. Zagros Thrust and Fold Belt has many large earthquakes. Great earthquakes have occurred along the Makran Thrust, including the 1945 M_W 8.1 event.

Figure 15.5 shows focal mechanism solutions of large earthquakes (M_W 6.0) along the eastern Arabian plate boundaries for the period 1980–present (Harvard CMT Project). Focal mechanisms are consistent with the broad-scale tectonics of the Arabian-Eurasian collision. We observe two main families of mechanisms on Fig. 15.5 (a) reverse faulting on planes oriented NW–SE and (b) strike slip mechanisms. The reverse mechanisms are parallel to the fold axes. Some of the reverse faulting mechanisms might be associated with a slight component of strike slip motion.

To the west to the Musandam Peninsula, Arabia is under thrusting the southern Eurasian margin along the Zagros Thrust. To the east of the Musandam Peninsula, convergence is much slower given the seismicity along the Makran coast. Strike-slip motion probably occurs along reactivated thrust planes associated with obduction of the Semail Ophilite (Oman Mountains). The Makran subduction is the region where the Gulf of Oman is continue to subduct under the southern region of the Eurasian plate. It differs from other subducting segments of the Arabian Plate in that it is an oceanic crust rather than continental crust that is being subducted beneath Eurasian Plate. This oceanic crust extends eastward to Owen Fracture Zone (OFZ) along the Indian Plate boundary.

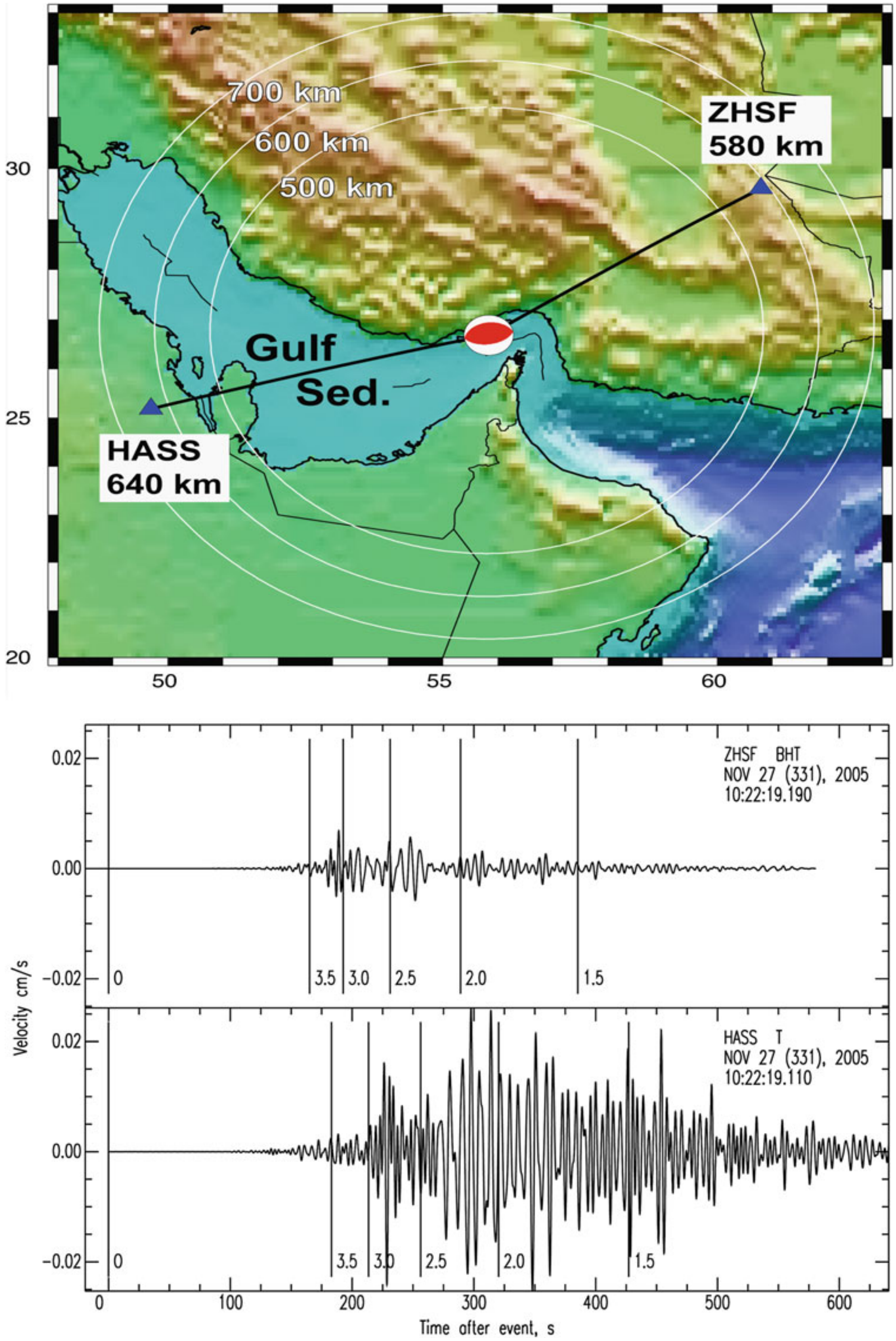


Fig. 15.4 Long-period ground motion recordings at nearly equidistant from ZHSF (*top*) and HASS (*bottom*) stations for 27 Nov 2005 Qeshm Island earthquake

Methodology

Data Sources

In the statistical characterization scheme for the seismogenic source zones of the eastern Arabian peninsula, different set of seismic data corresponding to two period of observation were utilized. The set of observation period were: 112–1964 AD and 1965–2003. The first set is labeled as historical data while the second set is instrumental data for purposes of discussion. The source catalogues from which the utilized seismic data are taken were the United States Geological Survey (USGS) PDE/EDR: 1963–2002;

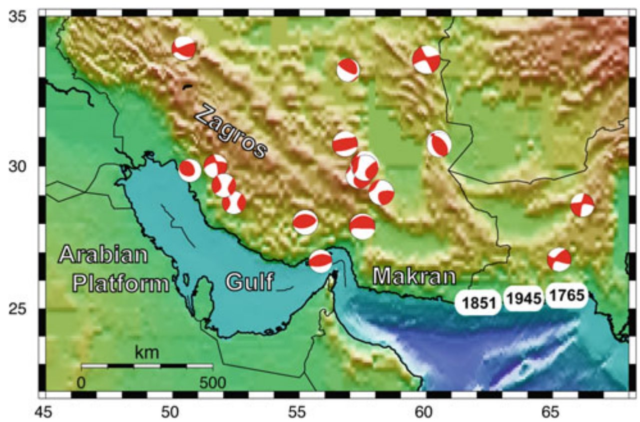


Fig. 15.5 Focal mechanism solutions of large earthquakes (MW 6.0) along the eastern Arabian plate boundaries for the period 1980–present (Harvard CMT Project)

the International Seismological Center (ISC): 1963–2002: (Ambraseys 1988) from 112–1963 AD; the European Mediterranean Seismological Center (EMSC): 1990–2002; the Seismic Studies Center (SSC) of King Saud University from 1986 to 2002, and the Kuwait National Seismological Network (KNSN) from 1997 to 2002. The seismic data obtained from these different seismic bulletins were merged and compiled to provide the main database for delineation and identification of the different seismogenic source zones in eastern Arabian peninsula and for statistical analysis. The compiled seismic data were likewise utilized in the seismotectonic correlation of the activity in each source area. Different types of magnitude such as surface-wave (Ms), body-wave (Mb), local (Ml), duration (Md), macro (Io), and others were converted to two types which are the surface-wave and body-wave to homogenize the main database. The purpose of homogenizing the database is due to the appropriateness of using the Ms in the concept of seismic moment, while the Mb for the seismicity parameters. Appropriate conversion relations were applied in these purposes (Al-Amri 1994; Al-Amri et al. 1998; Punsalan and Al-Amri 2002).

Data Treatment

A counter-checking of all the relevant data entries in the catalogues was undertaken to ensure non-duplication of the same earthquake events. For the overlapping years of the seismic data, limiting and distinguishing procedures for the space–time distribution of the data were followed to avoid duplication. To consider two or more data points as one single event should have less than 25 s difference in their origin time in a location of 200 km. For repetitive events, the USGS data is given preference in the selection.

Reduction of Cluster Events from the Database

Three processes were followed roughly in the reduction of clusters in the database. An initial logarithmic cumulative frequency (Log N) versus magnitude (M) plot is prepared from the original data. Using the larger range of magnitude from the data as a guide, an eye fitted or tentative line is drawn through the plotted data points. By inspection of the graphs, deviations of the data points can be observed. From the observations, the deviations in reference to the larger range of magnitudes can be reduced. The deviations can also be visualized from a space–time window. The space–time window can be roughly estimated from Utsu-Seki and Omori aftershocks equations respectively to reduce the anomalous deviations. In this approximate process of removal, presence of clustering can only be reduced, but not entirely eliminated.

Completeness of Database

Incompleteness of database cannot be avoided as there several factors and constraints that are involved. Absence and insufficiency, and or low detection capability of sensing seismic instruments in microseismic observation of earthquakes. Scarcity and inadequacy of physical factors involved in the macroseismic observation of seismic events. Completeness analysis of the data base was not conducted due to encountered constraints that can hamper the analysis. These are the subdivision of the database in two period of observation, the observed insufficiency of seismic data in most of the seismogenic source zones, and in view of zero number of seismic events in some magnitude intervals.

Missing Magnitudes

Missing magnitudes from the historical up to the instrumental period were not considered. The magnitude interval characterizing the missing magnitude for the historical data is large (1.5–2 units) as deduced from Ambraseys (1988), while for the instrumental events are less than 3. The effects of the distribution and inclusion of these missing events shall be similar to the presence of clustering in the database due to uncertainty in the appropriate magnitude values and an increase in the number of unwanted seismic events.

Seismic Modeling

The empirical and theoretical correlational methods and distribution function that were applied in the western part of Saudi Arabia seismogenic source zones are similarly utilized for the eastern section. This approach is conducted to maintain uniformity and homogeneity of results.

The seismotectonic modeling of the seismogenic source zones of eastern Arabian Peninsula were based on the following empirical and theoretical correlations. The empirical correlation was taken from observation of earthquakes occurring in tectonic structures. These are as follows:

Correlation Between Seismic and Tectonic Data

(a) Earthquakes do not occur everywhere, but only in definite tectonically active areas and in strong accordance with movement and deformation of geological structures. Globally, there were close relation between active faults and strong earthquakes, but the relations are not so strong in other areas characterized by less long term seismicity. The Earth is partitioned among large seismogenic and aseismogenic belts, which are apportioned further into smaller source zones. The seismogenic source zones have active faults at different depths, concealed in the depth or exposed on the surface. A seismogenic zone is therefore a main unit that determines the seismic conditions of a territory. The source zones are of different size and kind. In every zone occur earthquakes up to a definite value of the seismic parameters. These are due to varying size, degree of competency, and rate of movement, so that earthquakes correspondingly vary with the parameters.

(b) Major earthquakes occur along tectonically active source zones having large faults. The zones which divide geological units having different history of development and large difference in rates of movement are the most seismically active. The larger is the disturbed structure and the greater is its competency, the larger is the fault plane affected by the abrupt movements and the stronger will be the earthquake. Correspondingly, every group of homogeneously disturbed structure with definite competency and size has a definite ceiling of magnitude value. The more is the rate of structure movements along a fault and the less is the competency of these structures, the more rapidly the stress needed for an abrupt displacement of a structure along a fault is accumulated and the more often arise earthquakes of the maximum magnitude value for this structure. Every tectonically active source zone has its own rate of movement along it and corresponding frequency of earthquake occurrences.

(c) Geological structures move abruptly on faults along tectonically homogeneous active zone not simultaneously but alternatively in different places of the zones. Alternatively, in different places in this zone arise earthquake of maximum magnitude for this zone. When a source of an earthquake of certain maximum strength was recorded in this homogeneous active zone, then earthquake of the same strength can occur anywhere along this zone. In other word, the probability of such an earthquake can be extrapolated and interpolated along homogeneous tectonically active zones.

Correlation Between Earthquake Frequency and Mechanics of Faulting

The geological interpretation of the mechanism of an earthquake could possibly have started by Reid (1911) into quantitative terms (Lomnitz 1974). The concept was extended by others (Haskell 1964; Burridge and Knopoff 1964) to establish the theoretical and physical correlation between occurrence of earthquakes and deformation of tectonic structures. The most important parameter in mechanics of faulting as related to occurrence of a seismic event is the seismic moment Mo (Aki and Richards 1980; Burridge and Knopoff 1964)

$$\mathbf{Mo} = \mathbf{uAD} = \mathbf{uLWD} \quad (15.1)$$

where u is the rigidity, A is the fault plane area, L and W are the length and width of the fault respectively, and D is the displacement. The amplitude of the long period waves is proportional to the seismic moment. Since the surface magnitude (Ms) is calculated by measuring the amplitude of the long period wave, there exist a close relationship between Mo and Ms, and so with Mo, length and displacement arising from static similarity. For this study, the relationships are obtained empirically, which is a worldwide data collection of corresponding magnitude, moment, length, width and displacement. The empirical relationships that were obtained are as follows:

$$\mathbf{Log\,Mo} = [(\mathbf{1.62} \pm \mathbf{0.112})\mathbf{Ms} + \mathbf{15.1}] \pm \mathbf{0.3} \quad (15.2)$$

$$\mathbf{Log\,Mo} = [(\mathbf{2.54} \pm \mathbf{0.087})\mathbf{Log\,L} + \mathbf{22.56}] \pm \mathbf{0.31} \quad (15.3)$$

$$\mathbf{Log\,Mo} = [(\mathbf{2.61} \pm \mathbf{0.28})\mathbf{Log\,D} + \mathbf{26.32}] \pm \mathbf{0.44} \quad (15.4)$$

From (15.2–15.4), the following equations can be obtained when the standard deviation and standard error of estimate are not incorporated

$$\mathbf{Log\,L} = \mathbf{0.64Ms} - \mathbf{2.94} \quad (15.5)$$

$$\mathbf{Log\,D} = \mathbf{0.62Ms} - \mathbf{4.3} \quad (15.6)$$

Equation (15.2) is within the range of values (1.5–1.7) as obtained by Kanamori (1977), Hanks and Kanamori (1979), Scholz (1982). Equations (15.5) and (15.6) are close to Matsuda (1975) results which are 0.6, 2.9: and 0.6, 4 for the coefficients and constants respectively. The rupture is assumed to take place in the entire length of the homogeneous part of the fault or portion for segmented fault. The constraining equations for the fault length, dislocation, and magnitude are from (15.2–15.4)

$$52\mathbf{Log\,D} + \mathbf{7.25} < \mathbf{Ms} < 1.69\mathbf{Log\,D} + \mathbf{6.65} \quad (15.7)$$

$$55\mathbf{Log\,L} + \mathbf{4.36} < \mathbf{Ms} < \mathbf{1.6LogL} + \mathbf{4.94} \quad (15.8)$$

The magnitude frequency relation of earthquakes satisfies the empirical relation (Gutenberg & Richter 1954)

$$\mathbf{Log\,N} = \mathbf{a} - \mathbf{bMs} \quad (15.9)$$

where N is the number of magnitude Ms or greater, a and b the seismicity parameters. Equation (15.9) holds down to the level of micro-events (Mogi 1962; Scholz 1968) which indicates a fundamental physical understanding of the fracture process can be known if the relation can be explained completely. The Mo and Ms are both measures of the strength of an earthquake, so that (15.9) can be expressed in terms of Mo by means of (15.2). The theoretical consideration that the magnitude scale saturates at higher values of magnitude, but not with Mo is appropriate to substitute the seismic moment frequency relation for characterizing earthquake occurrences. From (15.2) and (15.9), a power law size distribution of earthquakes can be obtained (Wyss 1973)

$$\mathbf{N(Mo)} = \mathbf{Amo}^{(-\mathbf{B})} \quad (15.10)$$

$$\mathrm{A} = \exp[(\mathrm{a} + \mathrm{bc/d})\ln 10]$$

$$\mathbf{B} = \mathbf{b/d}$$

where a and b, c and d are the constant and coefficient in (15.9) and (15.2) respectively. From Wyss (1973), the total moment of a given earthquake population is the integral

$$\mathbf{Mo(tot)} = (\mathbf{AB}/(\mathbf{1} - \mathbf{B})\left[\mathbf{Mo}^{(\mathbf{1}-\mathbf{B})}\right] \quad (15.11)$$

where the upper and lower limits of integration are Mo(max) and Mo(min) as the maximum and minimum seismic moment in a given earthquake population respectively. In (15.10) it is assumed that the Mo(max) is attained when N(Mo) = 1, so that A = Mo^B. Likewise, in (15.9) the Mmax is also attained when N(M) = 1. If Mo(min) is insignificant compared to Mo(max), (15.11) becomes approximately equal to

$$\mathbf{Mo(tot)} = \mathbf{B}/(\mathbf{1} - \mathbf{B})\mathbf{Mo(max)} \quad (15.12)$$

From Wesnousky and Scholz (1983), the repeat time (Tmax) of (15.11) is

$$\mathbf{T(max)} = \mathbf{Mo(tot)}/\mathbf{Mo(g)} \quad (15.13)$$

where Mo(g) is the geologically assessed rate of moment release on a fault.

In (15.6), the recurrence time (Tmax) of an event with dislocation D is

$$\mathbf{T(max)} = \mathbf{D}/\mathbf{S} \quad (15.14)$$

where S is the linear average seismic slip rate.

The geologically assessed rate of moment release is not available in eastern Saudi Arabia. To be able to utilize the concepts enunciated in (15.9–15.14) for the correlation of regional seismicity to tectonics, there was a need to treat the 3 set of seismic data (historical, instrumental, recent) into one group in each seismogenic source zone in terms of Ms, to obtain the required parameters. The conversion equation was (Al-Amri et al. 1998a, b; Al-Amri 1994)

$$\mathbf{Ms} = \mathbf{1.14Mb} - \mathbf{0.9} \quad (15.15)$$

where Mb is the body-wave magnitude.

It has been indicated that the average geological moment release rate is almost the same as the average seismic moment release rate in 200–300 year of seismic data, and similar to the geological rate for 400 year of data. It is assumed then that the findings for seismic moment release rate have also the same similarities to the linear average seismic slip and or spreading rate. The period of observation in each source zone is counted from the earliest recorded year of the data up to 2003.

The geologically assessed rate of moment release is assumed to be equal to the ratio of the cumulative seismic moment release and period of observation. This assumption was also applied to obtain the linear average seismic slip or spreading rate. The average slip rate in each zone with sufficient seismic data could be compared to other findings obtained from different sources for validation. If the seismic slip rates are compatible to other results, presumably the seismic moment release rates would also qualify. When sufficient data are not available, the other alternatives could be to assume the applicability of the other parameters obtained in neighboring seismic source zones and or using (15.12).

The expected maximum magnitude in each seismogenic source zone is either taken from (15.9) [Mmax(S)], or the observed maximum magnitude Mmax(O) from the set of seismic data in each source zone, and or the estimated magnitude [Mma(L)] from fault length of the existing fractures in each respective seismogenic source zone. The expected Mmax(S) and or Mmax(O) are then correlated to fault length in (15.5) or dislocation in (15.6), and the magnitude from crustal depth (H) which is given as

$$\mathbf{Mmax(H) = 4Log\,H + 1.8} \qquad (15.16)$$

The corresponding feasibilities in (15.5), (15.6), (15.9) and (15.16) could indicate possible association and characterization of the most likely source of the given earthquake population in each seismogenic source zone. Earthquakes are not equally distributed in space–time, although probably the seismic events follow physical causalities which are not fully known. Therefore, at least the strongest earthquakes can be assumed to be independent random events. Considering the probability of occurrence of these seismic events in a time interval (t), and assuming the Poisson process as the appropriate probability function applicable in the source zones, then the probability of occurrence (Pr) of an event with return time (Tmax) is given as

$$\mathbf{Pr = 1 - exp(-t/Tmax)} \qquad (15.17)$$

Because there were different constraints encountered in the correlation processes such as scarcity of seismic data and inadequate information concerning fault parameters. It became necessary to refer to (15.17) as an additional data and basis in the decision processes. The time interval is assumed to be 100 years. Slemmons (1981) had described a characterization scheme for fault rate activity. The classification is as follows: (a) fault not active; (b) hardly active; (c) well developed geomorphologically (medium to high); (d) high; (e) very high; and (f) extremely high. The basis of the classification was the inverse of the linear slip rate as the constant slope of a linear relation between recurrence time and dislocation (Eq. 15.14) which is expressed in terms of magnitude. For slip rate of 10 cm/yr, the fault rate of activity is extremely high for magnitude range 4.8–9, for slip rate of 1 cm/yr, the fault rate activity varies from extremely high to very high for the magnitude range 4.7–9, for slip rate 0.1 cm/yr, the fault rate activity also varies from extremely high-to very high- to high for the magnitude range 4.7–9, for slip rate 0.01 cm/yr, the fault rate activity varies from very high- to high- to medium high for the magnitude range 4.7–9, and for slip rate 0.001 cm/yr, the fault rate activity varies from high-to medium high-to hardly active—to fault not active for the magnitude range 4.7–9.

Results and Discussion

Rationalization of Seismic Zoning

In the foreseeable future, there will be rapid growth of industrial development, increased population, and urban expansion. Experience has demonstrated that natural disaster, and earthquakes in particular have tended to become increasingly destructive since these affect a larger concentration of national properties and population, thus, generating calamitous incidents like the Cairo earthquake: 12 Oct 1992; Yemen earthquake: 28 Dec 1982; and Aqabah earthquake: 22 Nov 1995.

Particularly, three conditions determine the occurrence of an earthquake disaster. The first condition is the magnitude of the earthquake since small seismic events will not sufficiently generate severe ground shaking to cause extensive damage. The second condition is the closeness of the source of earthquakes, but under special conditions, earthquake disaster can occur at further distance (450 km). The third condition is dependent on the degree of earthquake preparedness.

Earthquake hazard depends not only on the seismicity of a region, but also on population density and economic development. Even though seismicity remains constant, both population and economic development are increasing rapidly. Identifying sources of vulnerability and taking steps to mitigate the consequences of future earthquake disaster are the most essential elements of disaster preparedness. Because the existing facilities represent the main earthquake risk, research and performance evaluation have much desire to be done in this critical area.

In order to reduce earthquake hazards in a rational way, it is necessary to have a clear understanding of the phenomena associated with earthquakes and their adverse effects. The key element in coping with earthquake hazard is the ability to assess seismic hazard. To make rational decisions in coping with earthquakes, it is necessary to know the answers to some questions related to:

1. Sources of destructive earthquakes.
2. Locations of earthquake occurrences.
3. Frequency of various size of earthquakes.
4. Nature of the severe ground motion near the source and its attenuation with distance.
5. Influence of local geology and site condition on the severity of ground shaking.

6. Types of earthquake hazards.
7. Main characteristics that define the damage potential of earthquake shaking.

Most regions that are threatened with earthquake hazards have conducted seismic hazard assessment through zoning maps with different seismic hazard level. Because each zone covers large area, the present map represents a crude average of the real seismic hazard in each zone.

A broad framework is utilized in the seismotectonic correlation and characterization of the source areas in eastern Saudi Arabia, due to the applied assumptions, empirical observations, theoretical considerations, and encountered uncertainties. The uncertainties are as follows:

1. Uncertainties in the identification of active and potentially active faults due to the low level of seismic activity among the seismogenic source zones.
2. Uncertainties in earthquake source mechanism among the seismogenic source zones due to the incipient stage of tectonic evolution in the region.

The characterization of the seismogenic source zones is composed of two parts. These are the brief discussions covering the possible association of each source zone to the tectonic and seismicity model of the areas contained in each source zone. The other part is a logic tree diagram for graphical description of the physical and seismicity parameters involved in seismotectonic correlation.

Two methods of approach were employed in the study. These are seismicity and fractures. Under the seismicity approach, the set of seismic data in each source zone was utilized to plot the magnitude-frequency relation, and for the estimation of the linear seismic slip and seismic moment release rates. From the frequency graphs, the respective seismicity parameters were determined for correlation to tectonic structures and probable earthquake source mechanisms. Under the second approach, the tectonic structures contained in each source zones were examined based on existing geological/tectonic maps for identification and association to the types of earthquake source mechanisms, and to the seismicity of the source area. Combination of the two approaches lead to the preliminary framework of a seismotectonic model for each seismogenic source zone.

From the findings, there were at most two types of sources for the tectonic model. These are the fault and area source. Under the fault source are the transcurrent and normal faults and their respective variations. Under the area source are the seismic events not directly associated to known presence of fractures or are off located, and or the sudden or randomly distributed dislocations of the ground within the source zones. Presumably, the causes of these seismic events under the area source are due to lateral and vertical structural discontinuities, or connected to some anomalous behavior of geophysical phenomena, and or undetected fractures.

For earthquake source mechanisms, there are also at most two types. These are the extrusion and transcursion mechanisms. The zones of extrusion are the seats of volcanic activity and high heat flow. Seismological and other geophysical data suggest that ridges and their continental extension are characterized by rifting, spreading, and other aspects of extensional tectonics.

Other earthquakes observed in eastern Saudi Arabia are those that probably belong to the intraplate population. Intraplate faults have slow slip-rate, shorter in fault length and more discontinuous, and have long recurrence time intervals. These characteristics of intraplate faults in relation to seismicity are mostly observed among seismic events that have occurred in some parts of the shield areas.

Generally, In the delineation and identification of the seismogenic source zones in eastern Arabian peninsula, some criteria were followed and utilized as guidelines. These are:

1. Seismological parameter—map of the space–time distribution of seismic events that could indicates the seismogenic provinces and seismoactive faults, and occurrence of large earthquakes, the level of which depends upon the seismic activity in the region.
2. Geological parameter—map of regional tectonics in the area which indicates the location of joints, faults, lineaments, and rift systems that are associated with seismic activities.

The boundaries of the seismogenic source zones are the results in the inter-agreement of these two criteria with the higher priority given to the spatial distribution of epicenters due to statistical needs in statistical analysis. The seismogenic source zones are selected that are composed of systems of faults or lineaments or rift systems whose boundaries do not traverse generally other tectonic units. Some of the seismogenic source zones are relatively large due to scarcity of earthquakes in this part of the eastern Arabian peninsula. From these considerations, there are twelve (15.12) seismogenic source zones (Fig. 15.6 and Table 15.1) that were identified and delineated.

Generally, the characterization of the seismogenic source zones of eastern Saudi Arabia is o composed of two parts. These are the brief discussions covering the possible association of each source zone to the tectonic and seismicity in each source area. There are two tectonic sources assumed in each source zone. These are the fault and area sources whose seismic activities are combined to determine the seismicity level using the frequency-magnitude relation. Under the fault source, all types of faults whenever possible are included. Area source is defined to be dislocations found to be off the fault source. The other part is a logic tree diagram for graphical description of the physical and seismicity parameters involved in seismotectonic correlation.

Symbolism is used in each logic tree diagram. These are as follow:

Mmax	expected maximum magnitude. Letter inside parenthesis means the source from which Mmax is taken. Letter S is for seismicity, O from observation, L from fault length, and A for assigned
a and **b**	seismicity parameters as obtained from cumulative frequency-magnitude relation and or Utsu (1965) and Aki (1965) maximum likelihood estimate method
ASSR	average seismic slip rate in mm/year
ASMoR	average seismic moment release rate in dyne-cm/yr
P	relative frequency or assigned probability due to distribution or location of seismic events in each source zones. Number inside parenthesis indicates assigned value
TrDmax	approximate recurrence time in years of the maximum dislocation corresponding to Mmax
TrMo(max)	approximate repeat time in years of an earthquake population with a Mmax
Hmax	crustal depth of structures corresponding to Mmax
Pr	estimated probability of occurrence in 100 years of Mmax

Zone 14 (Sirhan-Turayf-Widyan Basins)

Tectonic Setting

The tectonic units composing Zone 14 are: Harrat al Harrah, Umm Wuai graben, Wadi as Sirhan and At Tawil faults, Sirhan At Turayf and Widyan basins. During the late Triassic to early Jurassic, rifting occurred at the northern end of the Arabian plate. A new Neo-Tethys was created. A north trending seaway developed which is possibly a successor of the Paleozoic Widyan basin. In the late to middle Jurassic, a limited Palmyrid-trend rifting occurred and the extrusion of the Devora volcanics was concurrent with the tectonic activity. During the late Jurassic, the Levant region also shows uplift and rifting coincident with massive Tayasir volcanism that could be responsible for the formation of Harrat al Harah. Early Senonian uplift and inversion of older structures in the Levant caused deformations along the Syrian arc and the onset of faulting in the Azraq Graben in Jordan with possible extension in northern portion of Saudi Arabia. A major basin evolved into the Azraq graben, a part of which could be the Sirhan at Turayf basin.

Seismicity

Historical data shows that there is one event of magnitude 5 located at coordinates 32 N, 36E, and another one of magnitude 4 at 30 N, 42.5 E. The locations of these events seem to indicate that the first is generated by the Dead Sea transform fault, while the latter is within the vicinity of the Widyan basin.

Epicentral locations of instrumental data show that most of these are concentrated on Harrat al Harrah. However, the magnitude ranges of these events are from 2.5 to 3.8. The other events are scattered within the vicinity of Sirhan-Turayf and Widyan basins, and Wadi as Sirhan and At Tawil faults. The maximum magnitude of 5.4 in March 31, 1989 was observed to have occurred at Harrat al Harrah which could probably be due to fractures within the lava field.

Statistical analysis of the instrumental data using the cumulative frequency-magnitude relation show that the seismicity parameters have respective values as follow: $a = 3.13$: $b = 0.58$; $Mmax = 5.3$. The historical data is insufficient for statistical treatment.

Zone 15 (Najd Fault Zone)

Tectonic Setting

The major tectonic component of Zone 15 is the Najd fault system. The north, northeast, and northwest trending pattern of the faults, anticlines, and arches in central and eastern Saudi Arabia appears to have formed in two tectonic stages. These are the Precambrian Amar Collision between 640 and 620 million years ago (Ma), followed by the development of the Najd Rift System between about 570–530 Ma (Stoeser and Camp 1985). The Amar collision was between the Afif and Ar Rayn terrane. The collision took place along the north trending Al Amar Idsas suture bounded approximately from 22 to 25° north and 43–45° east whose longitudinal extension could be up to 29° north based from aeromagnetic map and possibly as far as the Zagros suture (Johnson and Stewart 1994). The Afif terrane formed the eastern edge of a series of terranes (Midyan, Hijaz, Asir), while the Rayn micro-plate corresponds to central and eastern Arabia and is bounded to the west by the Al-Amar island arc. Following the Amar collision, the entire Arabian-Nubian Shield appears to have started collapsing in extension. The extensional collapse

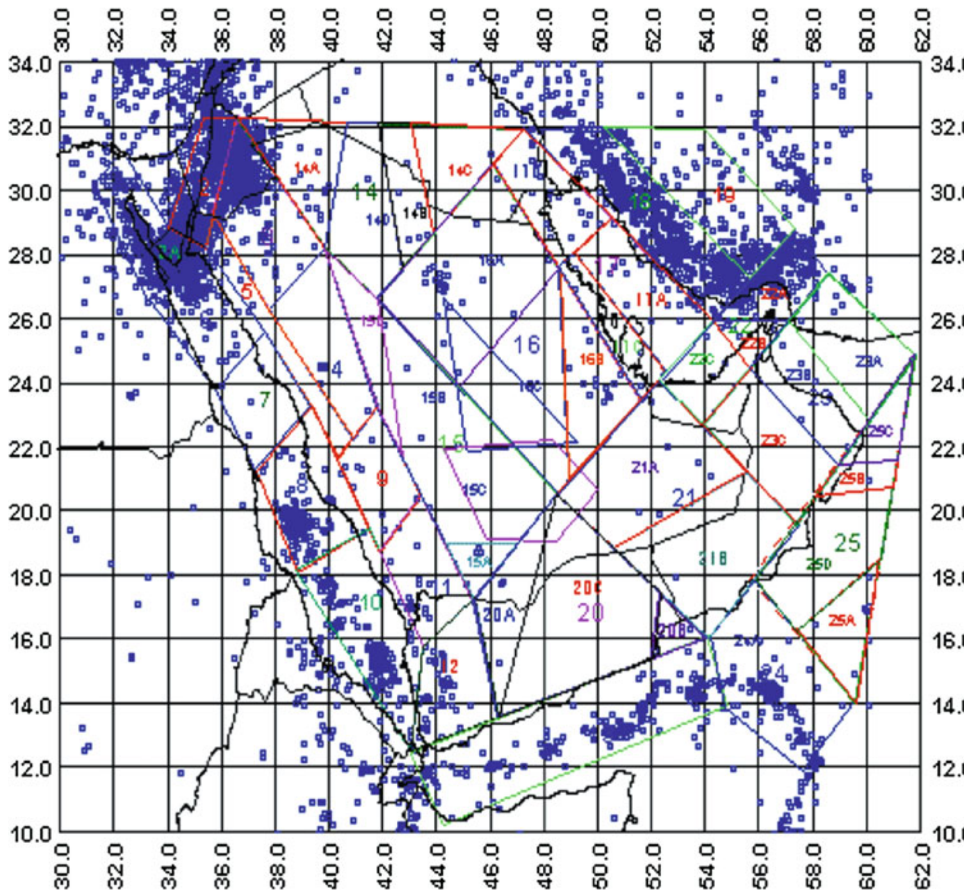


Fig. 15.6 Seismiciy and seismogenic source zones of the Arabian Peninsula and Adjoining Regions

culminated in the development of the regionally extensive Najd Fault System and its complimentary rift basins that make up the Najd Rift System.

The sinistral Najd fault system consists of three main parallel fault zones, each about 5–10 km wide, that dislocated the much older (680–640 Ma) Nabitah Suture by approximately 250–300 km (Brown and Jackson 1960; Brown Brown 1972; Moore 1979; Brown et al. 1989). The fault system has a width of about 300 km and an exposed length of 1,100 km. The dislocation on the Najd west (Ruwah, Ad Dafinah, Nabitah), central (Ar Rika), and east (Halaban-Zarghat) faults are about 120–150, 80–100, and 50 km respectively (Brown et al. 1989). The fault movement was brittle and the plate motion along the faults was kinematic (Moore 1979; Howland 1979). In the subsurface, the Najd fault system extends across the western Rub Al Khali basin as interpreted from seismic, gravity and magnetic data. Pull-apart basins that align with the Najd fault system show syn-rift layered seismic reflections and salt structures (Dyer and Husseini 1991; Faqira and Al-Hauwaj 1998).

Seismicity

No historical seismic events were observed to have occurred in this zone, and only 5 instrumental earthquakes were compiled. The observed maximum magnitude was 4.4 which had occurred in Nov. 6, 1997 in the vicinity of Kirsh gneiss and Ar Rika fault zone. The second event of lesser magnitude has a value of 4, occurring in 17 Aug 1997 also within the vicinity of the Ar Rika fault zone. Since there are only 5 seismic events, the Utsu-Aki maximum likelihood was utilized in the evaluation of the values of the seismicity parameters. The obtained values of the seismic parameters are: $a = 3.69$; $b = 0.74$; $Mmax = 4$. However, the estimated maximum magnitude from the seismicity parameters may not be the appropriate

Table 15.1 Seismicity parameters of seismogenic source zones

Zone no.	a	b	Mmax.	Fault source	Area source	Slip rate (mm/year)	Rate of seismicity
14	3.13	0.58	5.3	70 % strike slip	30 %	2.3	Low
15	3.69	0.74	4	75 % strike slip	25 %	NA	Low
16	3.54	0.64	5.4	30 % strike slip	70 %	1.3	Low
17	3.11	5.5	5.6	80 % strike slip	20 %	1.2	Moderate
18	6.11	0.9	7.0	81 % Reverse 19 % strike slip	–	4.4	High
19	5.06	0.79	7.0	90 % Reverse 10 % Strike slip	–	6.7	High
20	6.4	0.9	4.8	–	100 %	NA	Low
21	6.7	0.96	4.7	–	100 %	NA	Low
22	4.98	0.74	6.8	90 % strike slip	10 %	3.15	Moderate
23	3.8	0.71	5.9	75 % Reverse 25 % strike slip	–	1.5	Moderate
24	7.4	1.35	5.9	96 5	4 %	1.7	Low
25	7.55	1.3	6.1	40 % strike slip	60 %	1.6	Moderate

value should dynamic dislocations from the 3 faults in this zone occur. Assuming an average fault length of 166 km, the equivalent magnitude for this fault length is 8.0 as obtained from Eq. (15.1).

Zone 16 (Central Arabian Graben Zone)

Tectonic Setting

Zone 16 is roughly composed of the central Arabian graben and trough system; Wadi Batin and Abu Jifan fault; Summan platform, Khurais- Burgan and En Nala-Ghawar anticlines, Qatar Arch, and the Kuwait complex structures ranging from megascale, mesoscale, and microscale. The approximately 560 km compound graben system defines an arc concave to the northeast. It comprises six (15.6) major grabens and three (15.3) large synclinal troughs, together with subsidiary grabens and troughs. The major grabens are Majma, Al Barrah, Qaradan, Durma, Awsat, and Nisah. The Durma, Awsat, and Nisah lie entirely within the present region, which also includes 4 km of the eastern end of the Qaradan graben. The Majma, Awsat and Nisah grabens are compound structures. The Majma graben comprises many offset segments, whereas, the Awsat and Nisah grabens each consists of two overlapping segments. The three (15.3) large troughs are Buayja, Mughrah, and Sahba. Graben boundaries are defined high-angle normal faults commonly cutting the steep limbs of associated inward-facing monoclinal flexure zones. Trough margins are defined by inward-facing monoclinal flexures locally accompanied by subsidiary normal faults. Many grabens die out laterally through monoclinal flexures of decreasing amplitudes.

On the basis of stratigraphic and facies relationships, Powers et al. (1966) proposed that faulting on the central Arabian graben and trough system began in the Late-Cretaceous time and may have continued until the Eocene. The grabens developed between Late Cretaceous and the Late Quaternary, most movement being Paleogene age but succeeded by subsidiary Neogene and Quaternary movements.

Three (15.3) west-facing escarpments arranged in concentric arcs concave to the west dominate the topography. The western and highest escarpment, Jabal Tuwayq, is a double scarp. The western end is capped by the Tuwayq Mountain Limestone and the eastern end is capped by the Jubaila Limestone. The eastern end is the Jubayl escarpment capped of the Sulaiy Formation. The Durma basin lies west of the Tuwayq escarpment and the Kharj basin is situated between the Tuwayq and Al Jubayl escarpments.

The approximately 140 km Majma graben complex comprises many overlapping faults and en-echelon grabens replacing one another. The first is to the west and then to the east as the structure is traced from south to north (Powers et al. 1966). The southern segment trends 340°, while the northern segment trends 356°. Displacement on their boundary faults range from 150 to 200 m. From south to north, the graben complex cuts outcrops from the Dhruma formation to the Aruma formation. The 23 km Al Barrah graben trends 305°. Displacements on its boundary faults are estimated to range from 200 to 300 m (Powers et al. 1966). The graben is expressed by a relatively low dissected ridge that mainly exposes the Tuwayq Mountain limestone. The approximate length of the Durma-Nisah segment of the central Arabian graben system is 150 km and its width is about 25 km. The Nisah, Awsat, Durma, and Qaradan grabens are arranged en echelon. The Awsat and Nisah grabens are compound, each comprises two overlapping segment, the sense of overlap being the opposite of that displayed by the four grabens. Fault zones along graben margins commonly comprise a principal boundary fault, subsidiary antithetic or synthetic normal faults, and minor antithetic or synthetic extension faults, that is, small faults that result in layer-parallel elongation (Norris 1958).

The Qaradan graben is at least 12 km long and an average of 2.5 km width. The graben trends 310 degrees and its displacement on its boundary faults exceeds 400 m in the northeast. According to Powers et al. (Powers et al. 1966), the Qaradan graben is separated from the Durma graben by transverse fault striking 290°. The exposed length of the Durma graben is about 63 km. Its width is from 1 to 1.5 km. It trends 295°. Displacements on the boundary faults increases progressively westward. A few meters at the eastern end of the graben to about 100 m near longitude 46°27′ east, 330 m near longitude 46° and 17′ east, and about 400 m at the western end of the graben. The Awsat graben can be traced for about 90 km. It comprises two segments each 1–2 km wide. Powers et al. (1966) recorded an overlap of about 7 km, while present mapping shows the overlap of the graben boundary faults is about 25 km. The eastern segment lies north of the western segment Displacement on the high angle normal boundary faults are about 20-30 m close to the extreme western end of the structure, 200 m near (46°, 8′ east), 300 m in the central section (46°, 33′ east), and decline to about 50 m at the eastern end.

The Nisah graben is about 95 km in length and comprises two segments overlapping around 4 km along a common boundary fault near 46°, 36′ east. The 1.5–2.5 km wide western sement trends 290° at it western end and 280° at its eastern end. The eastern segment which is 2.5–3.5 km wide trends 275°. The Buayja trough is approximately 40 km in length. In the west, it is about 1 km wide and broadens to about 3 km in the east. Along most of its length, the trough forms a shallow topographic depression crossed by transverse wadis. The Mughrah trough is about 40 km long to the east from 47° and 19 min east. It has a gentler fold than the Buayja trough. The structural homolog of the Nisah graben east of longitude 47° and 10′ east is the Sahba trough. It has a broad structural and topographic depression of about 8 km wide. According to Brown (1972), it is possible that this structure extends further east up to the Arabian Gulf.

Seismicity

Seismicity of the area has been studied mainly on the data from the Seismic Studies Center (SSC) of King Saud University, the Bahrain Seismic Network (BSN), the Qatar Seismic Network (QSN), the Kuwait National Seismic Network (KNSN), and Ambraseys 1988 compilation. Historical data indicates that an earthquake of magnitude 5.8–6.0 was reported to have occurred in 1832 near the Al-Ghawar reservoir and Qatar arch. Instrumental data show that the Al-Ghawar area and its vicinity has experienced 86 earthquakes (2.5 < Md < 5.4) from 1965 to 1998. Most of these seismic events are located south to southeast of the Ghawar reservoir and the rest on the west of Qatar peninsula. Clusters of seismic events were also to occur in the Qassim area. Range of magnitude of these events is from 3 to 3.8. Instrumental seismicity indicates that an observed maximum magnitude of 5.3 has occurred in the vicinity of the central anticlines of the Arabian platform in 1 June 2002.

The seismicity of Kuwait reveals two main cluster of events. The first is around the Minagish-Umm Gudair oil field zone, and the second is around the Raudhatain-Sabriya oil field. The spatial correlation of earthquakes and oil fields suggest that the seismic events have been induced by oil production. The historical seismicity in this area indicates a magnitude 5.5 occurring north of Kuwait in 9 Sept 1903.

The historical data for this zone shows insufficiency for the determination of seismicity parameters, while from the instrumental data the values of the seismicity parameters are as follows: a = 3.54; b = 0.64; and Mmax = 5.4.

Zone 17 (Arabian Gulf)

Tectonic Setting

During the early to late middle Jurassic, the north trending Gotnia basin became established across the head of the Arabian gulf, possibly separated by the Rimthan arch from its southern extension, the Arabian basin. The Gotnia basin allowed direct access for the open Neo-Tethys far across the Arabian platform. In the middle Jurassic, incipient graben system with a northwesterly trend developed at the southern margin of the Arabian plate. They began as a terrestrial to continental infill of erosional lows or pre-rift structural depressions, and culminated as rift troughs containing shallow water carbonates in the middle Jurassic. At the beginning of the Cretaceous, global sea level was relatively high, and the remnant of the Gotnia basin underwent rapid subsidence in the eastern part. At the time of high sea level, a shallow epeiric sea inundated the eastern platform of the Arabian plate. During the late Paleocene to early Oligocene, the Hercynian structural trends of the central Arabian arch continued to modify the morphology of the foreland basins. This became progressively narrower as it was filled in, until it became structurally neutralized. During the Pleistocene, sea level was low, and east of the Arabian arch, the shallow epicontinental Arabian gulf began to take its present shape (Ziegler 2001).

Seismicity

The spatial distribution of epicenters shows a scattered location of earthquake events, except along the common boundary that separate Zones 17 and 18, where a thin line of NW trending concentration can be seen. The scattering seems to be distributed all over the basin. Some are located in the Zagros fold belt area that belongs to this zone. The Arabian gulf seismic zone is both historically and instrumentally active. A maximum magnitude of 5.9 is observed to have occurred in Aug. 16,1883 in the Zagros fold belt that belongs to the zone. A lesser event of magnitude 5.8 in March 6, 1956 was located in the basin. Instrumental data indicates that two earthquakes occurring in Nov. 7 1969 and in 13 Sept 2000 with the same magnitude value of 5 have occurred in the Zagros folded belt of the zone

Statistical analysis was conducted for the two period of observation separately using the cumulative frequency-magnitude relation due to sufficiency of seismic data. The obtained values for the seismicity parameters from the historical data were: $a = 4.15$; $b = 0.63$; $Mmax = 6.6$; while for the instrumental data gives: $a = 3.12$; $b = 0.55$; $Mmax = 5.6$.

A brief summary of the seismotectonic correlation for this source area is graphically provided by the accompanying cumulative frequency-magnitude relation and logic tree diagram (Fig. 15.7).

Zone 18 (Zagros Fold Zone)

Tectonic Setting

The primary tectonic unit in this source area is the folded zone of the Zagros Mountains. The Zagros mountains are a broad belt of NW–SE folded and faulted Paleozoic, Mesozoic, and Cenozoic rocks with orogenic movements occurring in Late Tertiary. Zagros mountain foreland is composed of gentle folded rocks, elongated, parallel and contemporaneous structure to the belt. The continued convergence of the Afro-Arabian plate relative to the Iranian blocks is partially accommodated by folding of the Zagros sedimentary cover and by high angle reverse faulting of the underlying Precambrian Arabian basement. The sedimentary cover is decoupled from the basement by the thick Infra-Cambrian Hormuz salt bed which acts as a detachment surface. The synchronous widespread deformation of the sedimentary cover and the basement is a unique feature for the Zagros region. The present basement faulting beneath the Zagros fold belt as due to re-activation of pre-existing normal faults as reverse faults in the Arabian continental margin is in conformity with assumption. Crustal models constrained by Bouger gravity anomalies indicate a dipping Moho about 1 degree to the northeast and increases to about 5° near the Main Zagros Thrust (MZT). The Moho depth increases from 40 km beneath the leading edge of the foreland basins (Mesopotamian Deep and Arabian Gulf) to 65 km beneath the MZT (Barazangi 1986).

Seismicity

The entire Zagros folded belt is the most active seismic area of the 12 seismogenic source zones. The folded zone is characterized by both shallow and non-shallow earthquakes. The earthquakes locations in this folded belt define a zone of about 200 km wide that runs parallel to its central axis. Most of the earthquakes are crustal seismic events that occur in the portion of the Arabian plate.

This seismogenic source zone is historically and recently active. Its historical data indicates that an earthquake of magnitude 5.7 has occurred in 21 March 1875. One 5.5 magnitude in 4 Feb 1934, and 3 magnitude 5.4 in 1925, 1939, and 1958 have occurred in this source zone. In 1972, a magnitude 6.1 has occurred which was followed by a magnitude 6 in 1976 in a span of 4 years. A survey of the range of magnitude in this zone is seen to be frequented many times with magnitude 5 and above.

Statistical analysis of the compiled seismic data using the cumulative frequency-magnitude relation gives values for the seismicity parameters for the historical period as: $a = 6.11$; $b = 0.9$; $Mmax = 7$; and for the instrumental data gives for $a = 6.28$; $b = 0.96$; $Mmax = 7$. A brief description and summary of the seismotectonic correlation for this zone is shown by the accompanying frequency magnitude relation and logic tree diagram (Fig. 15.8).

Zone 19 (Sanadaj-Sirjan Ranges)

Tectonic Setting

The main Zagros thrust with its crush zone and the Sanandaj-Sirjan ranges are the principal tectonic units in this seismogenic zone. From the late middle Eocene to early Miocene, the Arabian plate began to impact southern Asia, and the Zagros oregeny began. In the late Permian, continental rifting and spreading took place along the present day Zagros suture as the Neo-Tethys ocean started to form. The former intra-shelf basins, Lurestan and Khuzestan in Iran have been consolidated to form one long relatively narrow foredeep trough along the Zagros fold belt. Close to the

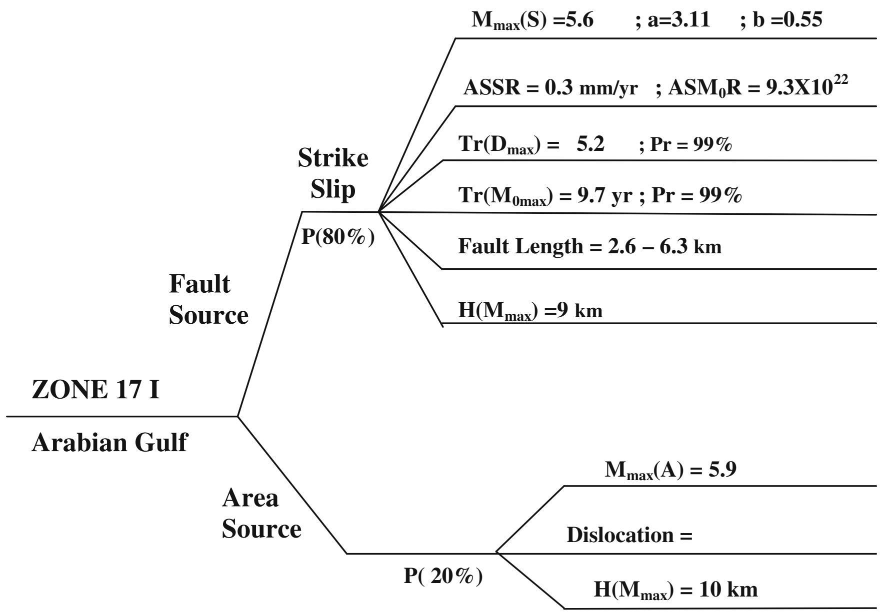


Fig. 15.7 Source zone logic tree for the Arabian Gulf

Zagros main thrust (MZT) silt and sandstones were deposited in the foredeep. Ophiolite nappes were emplaced along the MZT. During the Miocene, strong compression occurred as Arabia was driven into Eurasia. On the eastern flank of the Arabian plate, the thrusting of the Sanandaj-Sirjan zone onto the plate is evidence of the continental collision. As continent to continent collision continued, the Zagros oregeny intensified and thrust and folds belts migrated southwestward to their position in the Gulf region. Phases of compression led to the formation and deformation of the Zagros foredeep in front of the Zagros mountain belt. The Zagros foredeep (Mesopotamian basin) roughly corresponds to the zone between the Mesozoic unstable shelf to the west and the limit of the Zagros fold belt to the east.

Seismicity

The seismicity of this seismogenic source zone is governed mainly by two tectonic sources. These are the effects of under thrusting of the MZT by the Arabian plate and the convergence zone of southern Iran and Oman. However, the spatial distribution of earthquake epicenters in the MZT and the Sanandaj—Sirhan ranges is not as concentrated as the distribution in the Zagros folded belt and the convergence zone. Historically and recently this source area is seismically active. In 2 May 1963, a strong earthquake of magnitude 5.9 has occurred in the location of the MZT. From the historical data, it is seen that many seismic events of magnitude 5 and above have frequented this source area. In 21 June 1965 and in 12 April 1971 earthquakes of magnitude 6 have occurred. These two earthquakes are located near each other in the vicinity of the MZT and collision zone. It is also noted, that this period is frequented with seismic events whose magnitude values are 5 and above.

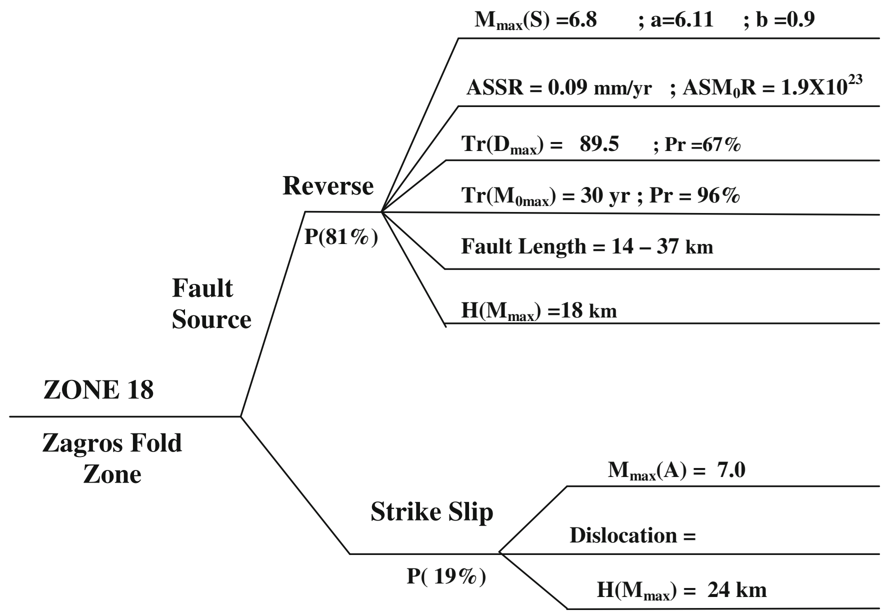
Statistical analysis conducted for the historical and instrumental data using the cumulative frequency -magnitude relation gives the following seismicity parameters values for $a = 5.06$; $b = 0.79$; $Mmax = 6.8$ of the historical data, and $a = 6.28$; $b = 0.96$; $Mmax = 7$ for the instrumental data.

Zone 20 (Eastern Yemen)

Tectonic Setting

The Marib-Shabwa basin is a west northwest-east southeast trending late Jurassic rift system which lies in southwestern Yemen. The orientation of the system corresponds to the Najd trend which probably exerted some control on the orientation of the Jurassic rift. It is part of an extensive system of basins which trend across southern Arabia and the Horn of Africa. To the east, the system extends almost to the island of Socotra. The structural framework of the Marib-Shabwa basin was established in Kimmeridgian-Tithonian times when the major period of rifting occurred. The rift widens considerably in the Shabwa area, and an important north–south (Hadramaut Trend) lineaments, such as the Shabwa arch and the Ayadin fault are present. This trend may be inherited from an underlying Proterozoic arc terrane suture. The Marib-Shabwa basin can be subdivided into several linked grabens and half-grabens. Basin geometry exercised a profound control on sedimentation by the central Marib-Shabwa basin both during syn-rift and post rift times. During syn-rift times, the deep half-grabens on

Fig. 15.8 Source zone logic tree for the Zagros fold zone



the basin margin and adjacent to the Central High trapped clastics in their axes and starved the central basinal areas. During post-rift times, the block-faulted topography controlled the direction of salt migration, with salt forming linear ridges overlying footwall highs. As a result, post-rift sedimentation was concentrated in a series of linear salt-withdrawal basins, overlying syn-rift lows.

Seismicity

Only two seismic events are recorded in this seismogenic source zone. One is historical and the other is instrumental. The historical event has a magnitude of 4.8 occurring in 21 June 1916 whose location is in the Hadramaut arches of eastern Yemen, while the instrumental data has occurred in 21 July 1997 and located also in the vicinity of the arches. No statistical analysis is performed for this seismogenic source zone.

Zone 21 (Rub Al Khali-Ghudun Basins)

Tectonic Setting

The most important tectonic elements in Oman are the three known Infracambrian salt basins. These are the Fahud and Ghaba salt basins in the north and the south Oman salt basin. Immediately to the west of the south Oman basin is the Ghudun-Khasfah high. It shows a north trending positive linear gravity anomaly that separates the south Oman basin from a gravity low to the west. It is thought that the western gravity low in the extreme southwest represents a fourth Infracambrian basin. This new basin is called Ghudun salt basin and appears to be comparable in areal extent with the Ghaba basin and analogous with the other Oman salt basins. The depth of the basement is estimated to be from 8 to 10 km.

The tectonic history of the Ghaba salt basin is dominated by compressional events ranging in age from late Pre-cambrian to Tertiary. The Ghaba salt basin is described as a push-down basin. The loading of the Oman mountains led to the development of foreland basins. Loading from the north resulted in a regional dip in that direction on which the Mesozoic carbonate section began to slide, resulting in a series of extensional faults of WNW orientation. This event allowed reactivation of the salt and many diapirs developed.

Seismicity

There are only 8 documented seismic events in this seismogenic source zone. Two were historical and 6 are instrumental. The maximum magnitude observed for the historical is 5.6 in 20 Aug 1954 which is located the Rub Al khali basin. The observed maximum magnitude for the instrumental data is 5 in 20 Aug 1997 which is also located in the basin. Due to seismic data constraint, statistical analysis is conducted mainly with the instrumental period of observation using Utsu-Aki (1965) maximum likelihood estimate of the values of the seismicity parameters. These are: a = 6.78; b = 0.96; Mmax = 4.7.

Zone 22 (Dibba-Bandar Abas Region)

Tectonic Setting

The primary tectonic units in this source zone are the Dibba fault and the Hormuz salt basin south of the Arabian gulf. The Dibba line in Oman marks a probable former transform fault. To its south, Cretaceous subduction began in Neo-Tethys 2, with back arc spreading leading to the development of what became the Semail Ophiolite nappe. Because of the very narrow microcontinent Jbel Qamar-Kawr ridge separating the Neo-Tethys 1 and 2, there was little effective resistance to the subduction process until the Maastrichian, when inability to consume the Oman sector of the Arabian continental process to a halt. With compressive stresses absorbed in Paleo-Tethys, late Cretaceous obduction in Neo-Tethys 1 and 2 did not lead to creation of the Oman and Zagros mountains.

In central Arabia, there was a slow but progressive infill of the intrashelf basins through repetitive shoaling upward carbonate cycles in the late Jurassic. At the beginning of the Cretaceous, global sea level was high and consequently most of the Arabian plate accumulated almost exclusively shallow marine carbonates. The Arabian basin was rapidly in filled, first by carbonates and later by terrigenous clastics. In the late early Cretaceous, extensive rudist banks colonized the shelf breaks to the intrashelf basins such as in the southern gulf. Far field stresses have thought to have resulted in the uplift and erosion of the western part of the Arabian shield and the supply eastward of large amounts of terrigenous clastics and shallow marine sands. The plate stress, combined with sufficient sediment loading served to trigger the growth of salt structures in the area of the southern Arabian gulf over which numerous rudist banks developed. At the southern portion of the Arabian gulf is where the Hormuz salt basin lies. The Hormuz is interpreted as a syn-rift sequence. This interpretation implies that the Hormuz evaporate basins were intra-continental (Ziegler 2001).

Seismicity

Two lines of spatial distribution of epicenters can be distinguishingly seen in this seismogenic source zone. The first which is a thin line of distribution is along the Dibba fault in northern Oman. The second has a wider zone of epicenter distribution. It is the convergence zone between southwestern Iran and northwestern Oman, a line known as Oman line that passes west of the Lut block in Iran. This seismic source area is both historically and instrumentally active. Two earthquakes of magnitude 6.4 occurring in 10 Jan 1897 and the other in 9 July 1902 were located in the convergence zone. Likewise, two earthquakes of magnitude 6.2 have also occurred in 21 March 1977 and 1 Apr 1977 in almost the same location. It is noted that this seismogenic source zone seems to have frequent earthquakes of above magnitude 6 and many seismic events above magnitude 5. Statistical analysis of the historical and instrumental data using the cumulative frequency-magnitude relation gives for the historical seismicity parameters the values for a = 4.67; b = 0.68; Mmax = 6.8; and for the instrumental data are: a = 4.98; b = 0.74; Mmax = 6.8.

Zone 23 (Hawasina-Makran Thrust Region)

Tectonic Setting

During the rift cycle one (Vendian/Infracambrian period), a series N–S to NE–SW trending basement high in Oman may have developed. These are the Ghudun-Khasfah high, the Anzaus-Rudhwan ridge, and the Makarem-Mabrouk high separating different basin segments. The event is associated with igneous activity (Oman mountains) and is followed by a thermal subsidence phase. Around 110 Ma, the Atlantic ocean begins to open, leading to the closure of the Neo-Tethys between the Afro-Arabian and Eurasian plates. A northeasterly dipping intra-oceanic subduction zone develops, accompanied by arc-spreading. At 93 Ma, this subduction complex collided with the continental crust of Oman creating the Zagros-Makran subduction zone. The initial uplift has been described as a mobile or stationary fore-bulge that preceded downwarping of the foreland ahead of the advancing thrust front. The second rift cycle which is also a compressional event as in rift cycle one occurred in the late Eocene to Miocene time. This event was responsible for the folding and short distance thrusting of the of the allochthonous units of the upper Cretaceous and Tertiary neo-authochthonous cover cover in the foredeep basins. The Huwayyah anticline is a unique example. The Tertiary compressional event caused reactivation of the late Cretaceous basal ramp fault to form the Huwayyah anticline and associated thrust strike-slip faults. The second event can be correlated with the Zagros oregeny in Iran. Two angle reverse faults are found in the western flank of the Huwayyah anticline. These are oriented in a NNW and ENE directions parallel and perpendicular to the fold of the anticline respectively. The main reverse fault is named Auha. A second reverse fault lies east of Auha. These faults probably originated as ordinary west dipping thrust on the western flank of the anticline. The displacement of the strike-slip faults are in the order of a few several meters and the sense of displacement suggests dextral movement.

The northern flank of the Sohar basin is limited by the Makran accretionary prism. This is an elongated and structurally complex thrust belt resulting from the subductionof oceanic basement under the Eurasian plate. The Makran is actively today and advancing southward at a maximum rate of some 10 cm/yr. Large overthrust anticline are recognized along the frontal thrust belt. Towards the core of the accretionary prism fault density increases creating a highly complex and deformed thrust belt.

Seismicity

Spatial distribution of earthquake epicenters in this zone is sparse. Some are found to be located in the Zagros-Makran subduction zone, in the gulf of Oman, the Hawasina thrust sheets, and in the Maradi fault zone. One earthquake event for each in the Hawasina and Maradi fault is located. Historical seismicity indicates that the observed maximum magnitude is 5.5 in 13 May 1905 which is located in the gulf of Oman. The instrumentally observed maximum event has a magnitude of 4.8 in 15 June 1977 and likewise is located in the gulf area.

Seismicity analysis for the historical and instrumental data using the Utsu-Aki maximum likelihood estimate method gives the following values for the historical seismicity parameters: $a = 3.8;\ b = 0.71;\ Mmax = 5.9$, and for the instrumental data: $a = 3.47;\ b = 0.76;\ Mmax = 4.8$.

Zone 24 (East Sheba Ridge)

Tectonic Setting

In the late Campanian-early Mastrichian, a rift developed between Seychelles and India. This rifting culminated in the Deccan volcanic event at approximately 64 Ma, when a new oceanic spreading zone which is the Carlsberg ridge developed. Above the Carlsberg ridge to the northeast is another ridge which is called the East Sheba ridge that connects the main trough of the gulf of Aden. The Sheba ridge is bounded by the Alula-Fartak trench to the west and by the Owen fracture zone to the east.

Seismicity

Epicenters distribution in this zone shows good correlation between seismicity and topography. The main line of epicenters follows the crest of the Carlsberg ridge that turns at 10.5 N, 57.0 E to a NNE direction, continuing in this orientation up to 13 N. At this latitude, it turns abruptly in a northwestward direction. The line of epicenters lies closely along the axis of the Sheba ridge to about 56.5 E where the seismic events are clustered. This zone is active historically up to the present time. The observed maximum earthquake in the histrorical time has a magnitude of 6.6 in 17 Aug 1899. This event is located off the main ridge axis. The instrumental maximum magnitude is 5.6 in 5 Dec 1981. Its location is likewise in the vicinity of the main ridge.

Statistical analysis conducted on the historical and instrumental data using the cumulative frequency-magnitude relation gives for the values of the historical seismicity parameters as follow: $a = 3.77;\ b = 0.52;\ Mmax = 7.3;$ while for the instrumental data analysis are obtained the values for $a = 7.94;\ b = 1.35;\ Mmax = 5.9$.

Zone 25 (Masirah Fault System)

Tectonic Setting

At the Cretaceous/Tertiary boundary, intra-oceanic north over south thrusting between the lower and upper ophiolitic nappes of Masirah island occurred. Along the east coast of Oman, largely offshore under Masirah bay and Sawqrah bay, a narrow gently folded foreland basin which is the Masirah trough was developed. The western margin is bounded by normal faults reactivating Mesozoic rift related faults. On its eastern margin, a wedge of ophiolitic and probably continental slope sediments is largely underthrusted below the eastern and uplifted part of the foredeep basin. To the south of the trough lies the Masirah transform fault.

Seismicity

The number of seismic events compiled for the historical and instrumental data are 7 and 4 respectively for this zone. The maximum historical event has a magnitude of 6.5 in Oct 10, 1900. Its epicenter is at 16 N, 60 E which is in the Owen fracture zone. For the instrumental data, the maximum magnitude is 5.2 in 15 Mar 1983. This event is also placed in the Owen transform fault. Only one event of magnitude 5.1 is found to occur in the Masirah thrust zone, while others can be considered as area source earthquakes or could be due to the influence of the Masirah and Owen transform faults.

Seismic parameters for this zone have been determined using the Utsu-Aki (1965) method for the historical and instrumental data. The values of the parameters are as follow: a = 7.55; b = 1.3; Mmax = 6.1 for the historical, and a = 3.64; b = 1.58; Mmax = 5.2 for the instrumental.

Conclusions

The Arabian Platform lies southwest of the Arabian Gulf. The lithospheric structure of the Arabian Platform has been derived from complete regional waveform modeling and surface wave group velocities. Waveforms from events in the Zagros possess clear *Pn*, *Sn* and *Lg*. The Arabian Platform has an average crustal thickness of 40 km with relatively low crustal velocities of 6.07 km/s and 3.5 km/s for P-and S-wave velocities, respectively. P-and S-wave velocities immediately below the Moho are slower in the Arabian Shield than in the Arabian Platform. Lower velocities in the Arabian Platform crust indicate a bulk felsic composition.

The Platform is covered by thick sedimentary cover (4 km). Sedimentary thickness on the Platform increases towards the Arabian Gulf, where it reaches a maximum thickness of nearly 10 km. The relatively slow and thick sedimentary structure plays a strong role in the surface wave dispersion of paths crossing the region.

Long-period ground motions are of concern in the Arabian Gulf region. Basin structure traps and amplifies surface waves. Large earthquakes in the Makran and Zagros could have wide spread, far-reaching damage. Long-period ground motions from distant earthquakes in the Zagros Mountains can be large enough to impact the eastern Gulf. large earthquakes in the Zagros can result in felt and possibly damaging ground motions at long-periods (1–10 s). Such ground motions are of concern for large engineered structures, such as tall buildings and long bridges with resonant periods in the same band (1–10 s).

Twelve seismogenic source zones were delineated and identified based on seismological and geological parameters with the higher priority given to the spatial distribution of epicenters. These source zones are composed of systems of faults whose boundaries do not traverse generally other tectonic units. Some of the seismogenic source zones are relatively large due to scarcity of earthquakes in the Arabian Platform.

References

Aki K (1965) Maximum likelihood estimate of b value in the formula log N = a − bM and its confidence limits. Bull Earthq Res Inst 43:237–240

Aki K, Richards P (1980) Quantitative seismology, theory and methods. Freeman and Comp, San Francisco

Al-Amri AM (1998) The crustal structure of the western Arabian platform from the spectral analysis of long-period P-wave amplitude ratios. Tectonophys V.2(90):271–283

Al-Amri AMS, Punsalan BT, Uy EA (1998a) Spatial distribution of the seismicity parameters in the Red Sea regions. J Asian Earth Sci 16(5–6):557–563

Al-Amri AM (1999) The crustal and upper mantle structure of the interior Arabian platform. Geophys J Int 136:421–430

Al-Amri A (1994) Seismicity of the southwestern region of the Arabian shield and southern Red Sea. J Afr Earth Sci 19:17–25

Al-Amri AMS, Punsalan BT, Uy EA (1998b) Spatial distribution of the seismicity parameters in the Red Sea regions. J Asian Sc 16: 557–563

Al-Husseini MI (2000) Origin of the Arabian plate structures: amar collision and najd rift. GeoArabia 5(4):527–542

Ambraseys N (1988) The seismicity of Saudi Arabia and adjacent areas. In: Report 88/11, 294p, Engineering Seismic. Engineering Seismology and Earthquake Engineering, Imperial College of Science and Technology, London, UK

Andrews IJ (1991) Paleozoic lithostratigraphy in the sub-surface of Jordan, Jordanian ministry of energy and mineral resources, national resources authority, subsurface geology. Bull 2:75

Barazangi M (1986) Deep structure of the Zagros collision zone: implication for earthquake hazard assessment and for the spatial distribution of oil fields in the Arabian gulf region. In: Proceedings of 3rd Arab Symposium on Earthquake Seismology, pp 35–45

Bender F (1982) On the evaluation of wadi Araba-Jordan rift. Jahrb Geol Bundesanstaldt Wien 4:3–20

Blood MF (2001) Exploration for a salt basin in southwest Oman. GeoArabia 6(2):159–176

Bramkamp RA, Ramirez LF (1958) Geologic map of the northern Tuwayq quadrangle, Kingdom of Saudi Arabia, scal2 1:500,000

Brown GF, Jackson RO (1960) The Arabian shield, 21st international geological congress, Copenhagen, pp 69–77

Brown GF (1972) Tectonic map of the Arabian Peninsula: Saudi Arabian Directorate General of Mineral Resources Arabian Peninsula map AP-2, scale 1: 4,000,000

Brown GF, Schmidt DL, Huffman AC (1989) Geology of the Saudi Arabian peninsula: shield area of Western Saudi Arabia, USGS Professional paper 560-A

Burridge R, Knopoff L (1964) Body force equivalent for seismic dislocation. Bull Seismol Soc Am 54:1787–1888

Dyer RA, Husseini M (1991) The Western Rub Al Khali infracambrian Graben system, Society Of Petroleum Engr. Paper 21396

Faqira MI, Al-Hauwaj AY (1998) Infracambrian salt basin in the western Rub Al Khali, Saudi Arabia. GeoArabia (Abstr) 3(1):p93

Gutenberg H, Richter C (1954) Seismicity of the Earth. Princeton University Press, New Jersey

Hank T, Kanamori H (1979) A moment magnitude scale. J Geophys Res 84:2348–2350

Haskell N (1964) Total energy spectra density of elastic waves for propagating faults. Bull Seismol Soc Am 54:1811–1841

Howland AF (1979) Tectonics of the Najd transcurrent fault system. J Geol Soc London 136:441–454 (discussion)

Johnson PR, Stewart ICF (1994) Magnetically inferred basement structure in central Arabia. Tectonophysics 245:37–52

Kanamori H (1977) The energy release in great earthquakes. J Geophys Res 82:2981–2987

Keilis-Borok V (1959) On the estimation of the displacement in an earthquake source and source dimensions. Ann Geofis 12:205–214

Lomnitz C (1974) Global tectonics and earthquake risk, development in geotectonic. Elsevier Science Publishing Company, New York

Looseveld RJH, Bell A, Terken JJM (1996) The tectonic evolution of interior Oman. GeoArabia 1(1):28–51

Matsuda T (1975) Magnitude and recurrence interval of earthquakes from a fault. J Seismol Japan Ser 2(28):269–283
Mogi K (1962) Study of the elastic shocks caused by the fracture of heterogenous materials and its relation to earthquake phenomena. Bull Earthq Res Inst 40:125–173
Moore JMcM (1979) Tectonics of the Najd transcurrent fault system. J Geol Soc London 136:441–454
Nolan SC, Skelton PW, Clissold BP, Smewing VD (1990) Maastrichtian to early tertiary stratigraphy and paleogeography of the central and northern Oman mountains. In: Robertson AHF, Searle MP, Ries AC (eds) The geology and tectonics of the Oman region, Geological Society of London Special Publication, vol 49, pp 495–519
Norris DK (1958) Structural conditions in Canadian coal mines. Geol Surv Can Bull 44:1–53
Noweir MA, Alsharhan AS (2000) Structural style and stratigraphy of the Huwayyah anticline: an example of an Al-Ain Tertiary fold, northern Oman mountains. GeoArabia 5(3):387–402
Powers RW, Ramirez LF, Redmond CD, Elberg EL (1966) Geology of the Arabian Peninsula, Sedimentary geology of Saudi Arabia: U. S. Geological Survey professional paper 560-D D1-D147
Punsalan BT, Al-Amri AM (2002) Scaling relations of earthquake parameters in the Red sea region. J King Saud Univ Sci 15(2):81–100
Reid H (1911) The elastic rebound theory of earthquakes. University of California, Department of Geology Bulletin, vol 6(19), pp 413–444
Robertson AHF (1987) Upper cretaceous muti formation: transition of a mesozoic carbonate platform to a foreland basin in the Oman mountains. Sedimentology 34:1123–1142
Scholz C (1968) The frequency-magnitude relation of micro-fracturing in rock and its relation to earthquakes. Bull Seismol Soc Am 58:399–416
Scholz C (1982) Scaling laws for large earthquakes: consequences for physical models. Bull Seismol Soc Am 72:1–14
Slemmons D (1981) A procedure for analyzing the activity of faults. In Proceedings of 3rd conference on basement tectonics, Denver, USA, pp 33–49
Stern R, Hedge CE (1985) Geochronological and isotopes constraints on late Precambrian crustal evolution in the eastern desert of Egypt. Am J Sci 185:97–127
Stoeser DB, Camp VE (1985) Pan African microplate accretion of the Arabian shield. Geol Soc Am Bull 96:817–826
Utsu T (1965) A method for determining the value of b in a formula $\log n = a - bM$ showing the magnitude-frequency relation for earthquakes. Geophys Bull Hokkaido Univ 13:99–103
Wesnousky S, Scholz C (1983) Earthquake frequency distribution and the mechanics of faulting. J Geophys Res 88:9331–9340
Wys M (1973) Toward physical understanding of earthquake frequency distribution. Geophys J Res Astr Soc 31:341–359
Ziegler MA (2001) Late permian to Holocene paleofacies evolution of the Arabian plate and its hydrocarbon occurrences. GeoArabia 6(3):445–504