EARTHQUAKE HAZARD ASSESSMENTS FOR SOUTHERN RED SEA REGION

Prepared by: Amro Essa Al-Essa

Supervisor: Dr. Sattam A. Almadani

Department of Geology and Geophysics
College of Science - King Saud University

Riyadh, Saudi Arabia
Rajab, 1435 A.H.
May, 2014 A.D.

ABSTRACT

There are a great number of historical and recent earthquakes that have occurred in the southern part of the Red Sea between Latitudes 14^{o}-19^{o} N and Longitudes 39^{o}-45^{o} E in the period of 200-2005 A.D. with magnitudes ranges from $2 \leq M \leq 8.0$. The area has a complex geological structures and tectonics. This study presents the seismic hazard assessment for the southern part of the Red Sea depending on the results of the epicentral allocation of both historical along with instrumental earthquakes from the study done by Almalki and Alalmri in 2009. The results also demonstrate a wide-ranging correspondence with the regional geology and tectonics of the area. Additionally, seismic zones characterizations were performed rely on magnitude distribution.

ACKNOWLEDGMENTS

I would like to extend my heartfelt thanks and gratitude to each and every one who assist me throughout the end of my graduation project. I would like to begin by thanking Allah and then my parents for their tremendous and nonstop support. My thanks go to my academic advisor, Dr. Sattam Almadani, for giving me his full support and valuable advices. I would like also to thanks Prof. Kamal Abdel Rahman and Prof. Ali Kamel. As well as, I thank everyone who gave me help, advices, and suggestions during this period. Finally, I hope to accomplish the most important objectives of this project.

TABLE OF CONTENTS

TABLE OF FIGURES

1. INTRODUCTION

In general, the Red Sea, a young divergent mid-oceanic ridge, is a region of international interest for observation and study of rifting and subsequent drifting continents [Al-Saud, 2008]. It is structurally multipart, having features of unusual ages, styles, and trends. The study area is sited between Latitude 14^{o}-19^{o} N and Longitude 39^{o}-45^{o}E (Figure 1.1). It can be described by a variety of topographic features as plateaux of Hejaz and Asir (1300-2000 m above Sea level) extends along the western coast of Saudi Arabia [Almalki and Alamri, 2009]. The Northern Yemen has a complicated topographic regions as: 1) Coastal plain region, extends along the coast of Yemen, 2) Mountain highs region extends from the northern to southern Yemen borders, 3) Mountain basins region that includes the main basins and plains within the mountain highs [e.g. Yarim, Dhamar, Sadah] and finally plateaux belt which present in the east and north of mountain highs region [Almalki and Alamri, 2009]. The Red Sea can be divided into three physiographic regions: 1) The narrow continental margins, 2) The main trough, and 3) The deep axial trough [Drake and Girdler, 1964]. South of Latitude 24^{o} N, a deep axial trough appears in the main trough.

The Red Sea, which is a flooded rift valley created by the pulling apart of the African and Arabian continental plates, maintains a critical link between the Indian Ocean and the Mediterranean Sea. It is relatively

younger and extends almost in a South-Southeast to North-Northwest direction between latitude 12°-30° N and longitude 32°-44° E (Figure 1.2). The Red Sea is about 1930 km long average width is 270 km and it narrows at the strait of Bab al Mandab to about 27 km [Edwards, 1987]. The maximum width is about 300 km in the southern sector near Massawa, is a city on the Red Sea coast of Eritrea located at the northern end of the Gulf of Zula. The average depth is approximately 520 m and a deep trench width a maximum depth of 2920 m is continuous from 14^0 N to 28° N in the middle of the Red Sea. The surface area is ~ 0.44 x 10^6 km^2. The Gulf of Suez has a relatively flat bottom with a depth in the range of 55 – 73 m.

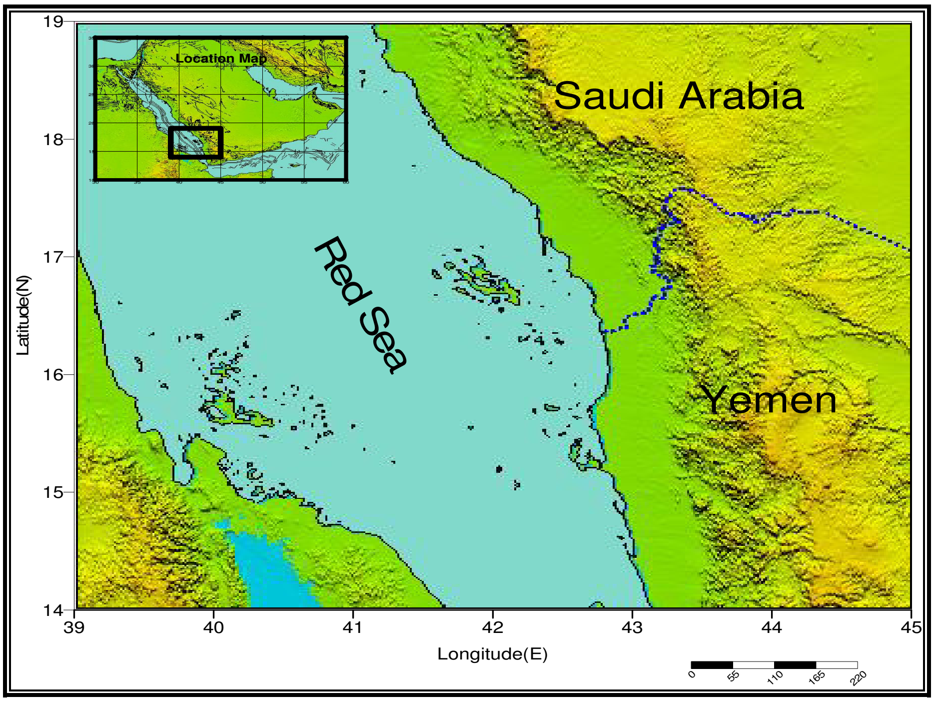

Figure 1.1 Topographical map of the study area [after Almalki and Alamri, 2009]

The Red Sea has been an important trade rout throughout human recorded history, linking the trade goods of the east to the historical markets of Egypt. When Suez Canal was completed in 1869, the connection became direct, and now the Red Sea is one of the important shipping routes in the world. The Red Sea can be divided into three physiographic regions; the narrow continental margins, the main trough, and the deep axial trough [Darke and Girdler, 1964]. South of latitude 24° N, a deep axial trough appears in the main trough. Like the Mediterranean, the Red Sea is an almost enclosed basin. The only significant is the strait of Bab al Mandab connecting the south of the Red Sea to the Gulf of Aden. The shallowest sill over which the deep water passes is about 140 m deep.

The topography rises steeply above the shores of Aqaba in the north (Figure 1.3). The bottom topography of the gulf is irregular; depth reaches 900 fathoms. The Gulf of Suez, by contrast, is filled with sediments to a depth about 50 meters. Its shores are bordered by sedimentary lowland similar to that of the red sea. The only major inconsistency in the borderland pattern of the red sea itself is the Afar plain, extrusive igneous lowland which borders the southwestern shore. This plain fills a large triangular area between the sea and the high-land of Ethiopia and Somalia. The two high lands join at the southwest corner of the plain and then continue inland toward the east African rift zone. An

important interruption of the Afar plain is a horst of basement rocks and sediments which runs parallel to the Red Sea coast. Toward the east, the Gulf of Aden shores diverge toward the Indian ocean at a small angle (6-9 degrees) like that of the red sea shores.

Figure 1.2 Map of the Red Sea [after Public Domain Maps from University of Texas Libraries]

The Red Sea bottom is rough except below the shelves. It has a distinguishable pattern of depth—wide trough and narrow shelves in the north; wide shelves and narrow median valley in the south. The mean depth is on the order of 500 meters. Sediment thicknesses rang up to several kilometers where measured below the shelves and trough. They are much disturbed by faulting below the trough. The topography of the Red Sea is highly irregular, and steep sides' hills are common. The bottom shows an abrupt descend from about 60 m in the coral reef zone to more than 700 m in the area beyond the reef formation and then the depth gradually increase to seaward direction. The bottom is characterized by the presence of isolated elevation-like structures [Behairy and El-Sayed, 1983]. Accordingly, the aim of this study to evaluate seismic hazard prospective in terms and the site response characteristics at big cities lie within this area to mitigate the direct impact of earthquakes on the human life and buildings within the area.

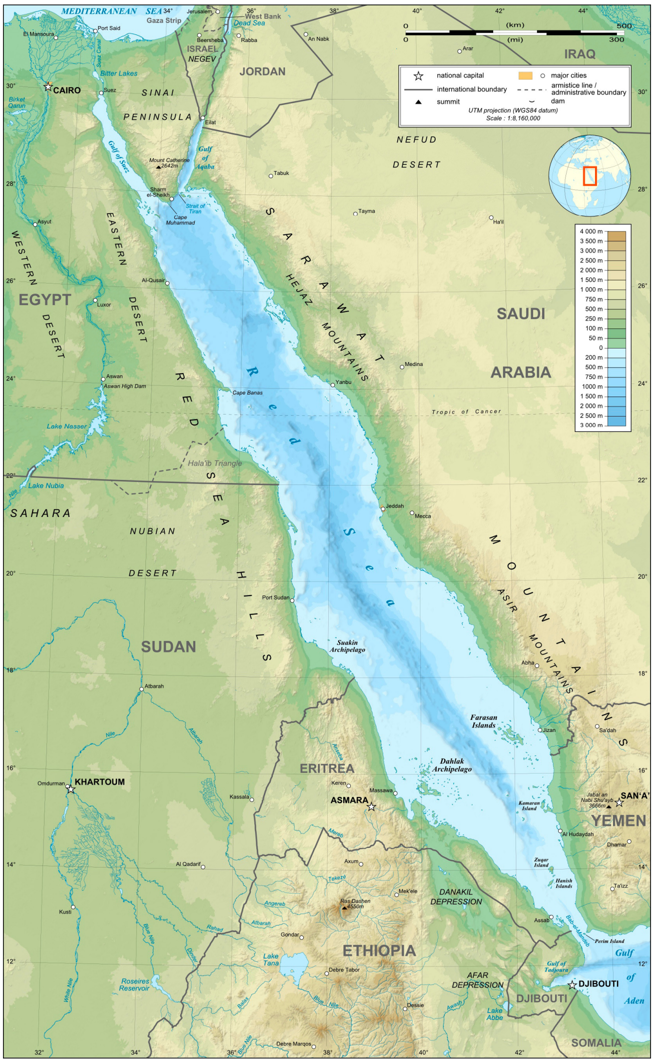

Figure 1.3 Topography of the Red Sea [after www.wikimedia.org]

2. GEOLOGICAL SETTING

In late Tertiary the great rift-fault systems of Africa and Red Sea also began to take on their present form, although movements on these faults may have started somewhat earlier. The Red Sea was developed by three tectonic movements led to formation of the southern part, northern part and Red Sea itself. The southern part the Red Sea connected to Gulf of Aden, which trends ENE-WSW, in Afar area was injected magma upward from the upper mantle and led to the formation of the regional joints in this within 20 to 30 my [Almalki & Alamri, 2009].

The Red Sea-Gulf of Aden rift system is generally interpreted as an example of an embryonic and young ocean basin formed by the break up of a continent (Figure 2.1). A number of plate tectonic reconstructions have been suggested for this region [Freund, 1970; McKenzie *et al.,* 1970; Girdler, Darracot, 1972; Le Pichon, Francheteau, 1978; Richardson, Harrison, 1976]. The central Red Sea, between 20° N and 25° N, is transitional between the southern Red Sea where an axial rift valley with large magnetic anomalies is almost continuous, and the northern Red Sea where the axial valley and associated magnetic anomalies are absent. The axial trough with strong magnetic anomalies of the southern Red Sea is generally interpreted as due to emplacement of oceanic crust with initiation of spreading ranging from about 1 to 5

million years ago [Vine, 1966; Allan, 1970; Phillips, 1970; Kabbani, 1970; Girdler *et al.,* 1974; Roeser, 1975].

Figure 2.1 Map of Red Sea and the plate boundary and direction of movement [after www.usgs.gov]

Rifting in the Red Sea and Gulf of Aden continues an episodic process that began in the Permian: the peeling away of strips of the Gondwana part of Pangaea along Paleo- and Neotethyan continental margins [Stampfli et al., 2001]. It is in reality more complex than this, because collision of Arabia with Eurasia and the emergence of the Afar plume also played important roles in the kinematics and dynamics of the region. Although the Red Sea and Gulf of Aden share in many respects a common tectonostratigraphic history due to their common role in the

separation of Arabia from Africa, the kinematics and dynamics of these rifts were very different.

The Red Sea started with rift-normal extension, and switched to oblique-rifting much later. Its oceanic rift developed completely within continental lithosphere, with-out any connection to the world mid-ocean ridge system. By integrating studies of both rifts, an informative view of the onset of continental break-up can be obtained. The Gulf of Aden and Red Sea basins tectonically link through Afar. The geometry of this connection is dramatically illustrated by compilations of seismicity [Ambraseys et al., 1994; Hofstetter and Beyth, 2003]. The Red Sea rift initially included the present Gulf of Suez and the Bitter Lakes and Nile Delta region on the continental margin of North Africa [Bosworth and McClay, 2001].

The local geometry of the early Red Sea rift was strongly influenced by pre-existing basement structures, and as a consequence followed a complex path from Afar to Suez. Each segment of the rift was initially an asymmetric half graben, with well-defined accommodation zones between sub-basins. In the Gulf of Aden, the positions of accommodation zones were strongly influenced by older Mesozoic rift basins. Early rift structures can be restored to their original contiguous geometries along both the Red Sea and Gulf of Aden con-jugate margins. In both basins, present-day shorelines restore to a separation of 40–60 km

along most of their lengths. The initial rift basins were 60–80 km in width. The Red Sea formed during the Eocene–Oligocene period and is one of the world's youngest oceanic basins [Al-Amri 1995]. The boundary between the African and Arabian continental plates follows the principal axis and runs along the entire length of the sea floor (Figure 2.3). As the two continental plates are slowly moving apart, the land beneath the Red Sea falls within an active seismic area and experiences frequent earthquakes. The Red Sea is a typical oceanic rift dating back to 5.7 Ma ago [Roeser 1975] and was one of the first areas to be interpreted in the framework of plate tectonics [McKenzie et al. 1970].

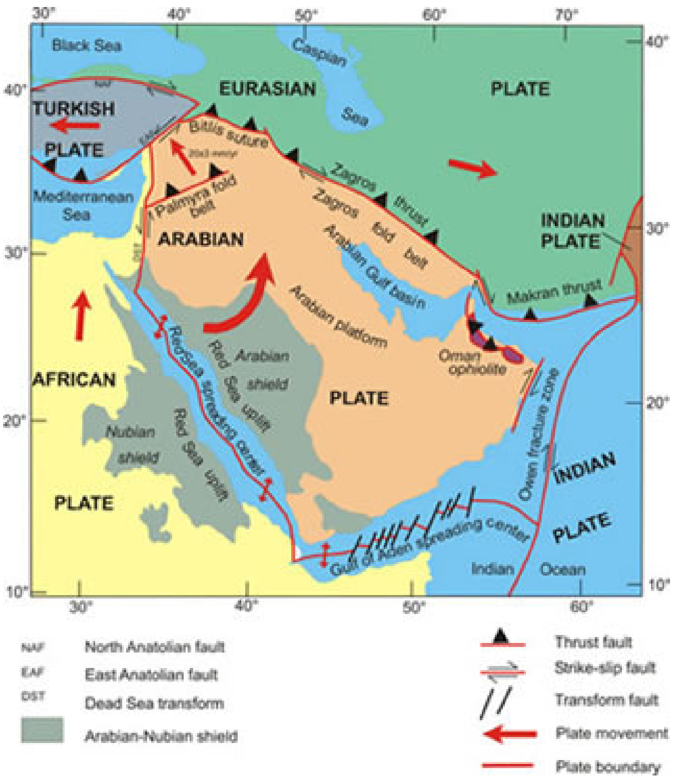

Figure 2.3 Map of Red Sea and the plate boundary and direction of movement [after Hussein, H., 2011]

3. HISTORICAL SEISMICITY:

The Red Sea area has experienced more than a few main historical earthquakes (Figure 3.1). In 1121, an earthquake occurred along the main trough with a magnitude of 6.9 that was felt over a wide area and caused damage to structures located 300 km apart such as Madinah and Makkah [Ambraseys et al. 1995]. Between 1884 and 1980, 24 earthquakes with magnitudes between 6 and 6.9 struck the Red Sea. On 31 March 1969, an earthquake of magnitude 6.9 occurred at the Gulf of Suez [Al-Ahmadi et al. 2013 and Abdel-Rahman et al. 2009] while on 13 December 1982, the highlands of Dhamar in Yemen (160 km to the Red Sea) were hit with an earthquake of magnitude 6.0, killing 2,800 people, injuring a further 1,500, and leaving around 400,000 people homeless [Choy and Kind 1987]. The largest event of moment magnitude (Mw) 7.1 took place on 22 November 1995 at the Gulf of Aqaba, causing structural damage to buildings in several cities along the gulf coast [Al-Tarazi 2000].

According to the research in the published compilations of historical earthquakes for the Middle East [Poirier and Taher, 1980; ElSinawi, 1983 & 1986; Ambriaseys and Mellvile, 1983; Ambriaseys et al., 1994], the historical seismicity is of the swarm- type and mainly related to the volcanic eruption along the western Arabia. There are about 78 earthquakes have occurred in the area in the period from 200 till 1900. Most of earthquakes are concentrated around Sanaa- Aden along the Red

Sea and this due to the past distribution of population density in Arabia. Some of the historical earthquakes have occurred on offshore and these earthquakes were felt on the land which reflects to continuation of marin tectonics into the land. There are about 22 earthquakes have occurred in the period from 1900 till 1964 with magnitude ranges between 4 and 6.3. Most of historical earthquakes seem to the correlate with the general tectonics of the region [El-Isa& Al-Shanti, 1989]. A major characteristic of the epicenters is a NW alignment, parallel of the axis of the Red Sea where some instrumental earthquakes occur as well. A perpendicular alignment is also observed.

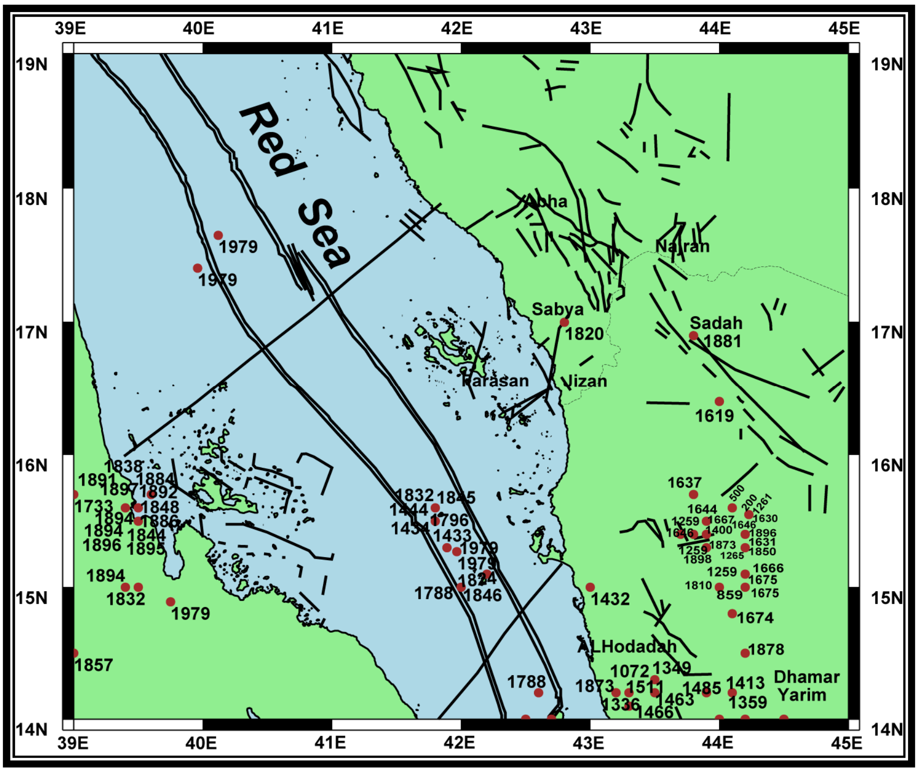

Figure 3.1 Historical Seismicity within the area of study [after Almalki and Alamri, 2009]

Many of earthquakes has recorded in the Red Sea, for example the period 1913–86 some 135 earthquakes ($3 \leq M \leq 6.9$) occurred in the Red Sea and western Arabia between latitudes 14° and 27.2°N (Figure 3.2). In the same period, 49 earthquakes ($M \leq 6.9$) and 247 earthquakes ($M \leq 4.9$) are reported to have occurred in the Gulfs of Suez and Aqaba respectively. Twenty-three historical earthquakes are reported to have been felt in the region with intensities IV-IX and a few more with unassigned intensities. The epicentral distribution of both instrumental and historical data and their characteristics show a general correlation with the regional geology and tectonics. Sixty per cent of the total energy released from all instrumental earthquakes is released from earthquakes epicenters within the spreading zone. Concentrations of activity are seen where the spreading zone is intersected by the NE transform faults and where this zone shifts in direction. Much of the seismicity of this region is of the swarm type and volcanic-related. Both instrumental and historical data show an apparent lower seismicity in the northern Red Sea region between latitudes 22° and 27.2°N, but the whole region is of a noticeable seismic risk that is mostly associated with regional land faults, some of which are continuations of the Red Sea transform faults.

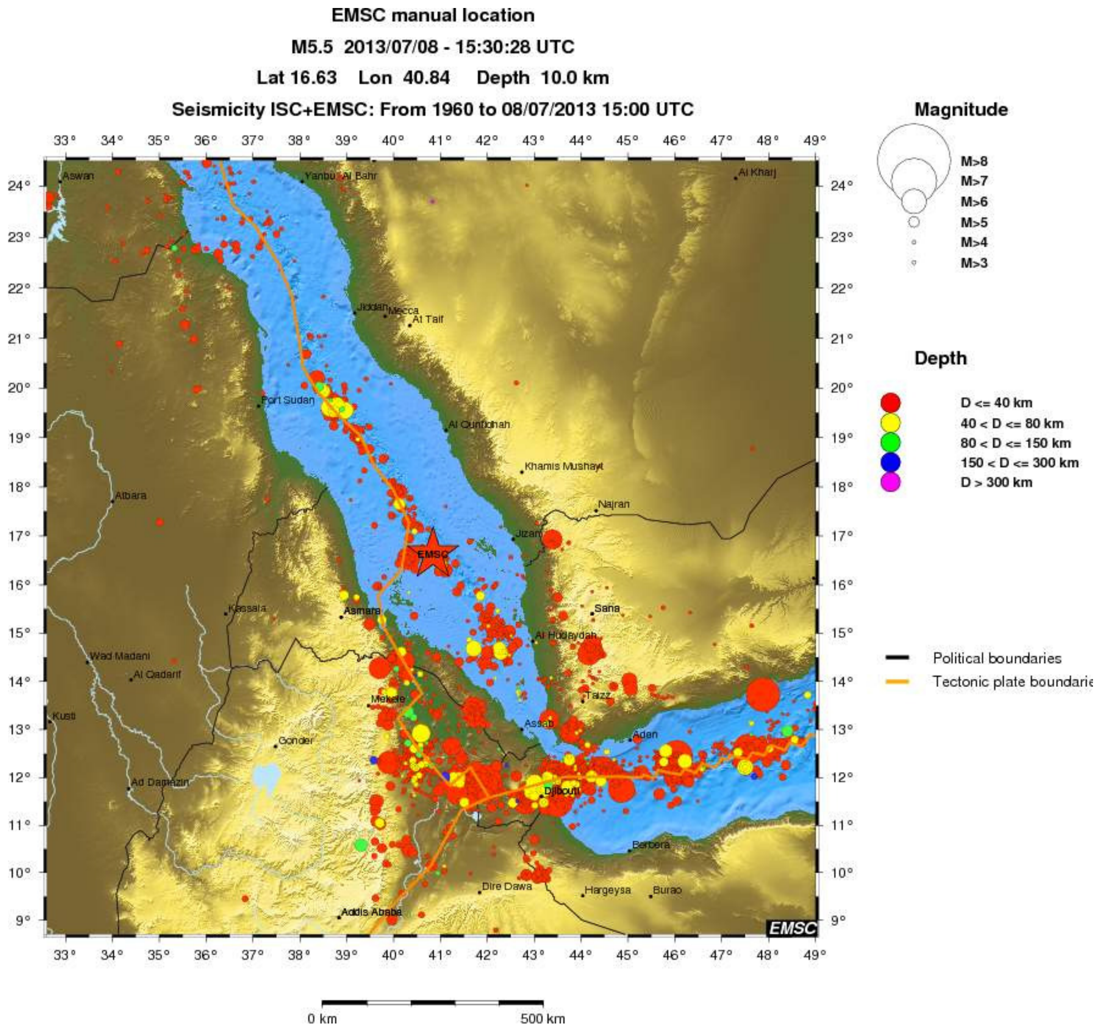

Figure 3.2 Recent seismicity of Red Sea [after www.emsc-csem.org]

4. PREVOIUS STUDIES:

The previous studies showed that the Arabian plate subjected to the tectonic movements since Pliocene age, where great lateral movements started to move the continental blocks toward the north (40km) of the Arabian plate with relative to the African plate and formed narrow strait of Bab El-Mandeb [Abdel-Gawad, 1969]. These movements continued to the northeastern direction along the Gulf of Aqaba (150 km) [Freund et al., 1970] in the Middle Miocene age. Left-Lateral movement (40 – 45 km) for the Miocene rocks in Sinai area and led to the formation of the axial trough of the Red Sea. The spreading rate was asymmetric during these movements along the Red Sea as indicated from the change in the width of the axial trough. As a result of these movements a more complicated structures were formed including major faults in the south of Saudi Arabia and causing many earthquakes.

Depending on the geological, geophysical studies as well as the distribution of recent earthquakes in the Red Sea and comparison with the location of earthquakes in Tahoma and Arabian Shield, it is noticed that there is a possibility for the extension of some faults from offshore into the land especially between 16.3^{o} – 17.4^{o}N to the northeastern of Abha and it is considered that these faults are responsible for the western Abha earthquake 1408 H (5.2 magnitude). The northeastern faults were formed due the separation of Arabian plate from African plate in the northeastern

direction. Based on the Heat Flow Density (HFD) studies [Makris, 1986 & 1989], the type of crust can be differentiated.

From the historical and instrumental earthquake studies [Al-Amri, 1994] it is noticed that most of earthquake have occurred along the axial trough of Red Sea. But there are four earthquakes in 1941 (Mb=6.25), 1955(Mb=5.7), 1962 (Ms=4.7) and 1928 (Mb=6 north Yemen) have occurred away from axial trough of Red Sea [Langer et al., 1987]. Some seismic hazard studies [Barazangi, 1981 and Thenhaus et al., 1986] carried out for the southern Red Sea based on the probabilistic approach.

5. SEISMIC HAZARD:

Seismic hazard refers to the study of expected earthquake ground motions at the earth's surface, and its likely effects on existing natural conditions and man-made structures for public safety considerations; the results of such studies are published as seismic hazard maps, which identify the relative motion of different areas on a local, regional or national basis (Figure 6). With hazards thus determined, their risks are assessed and included in such areas as building codes for standard buildings, designing larger buildings and infrastructure projects, land use planning and determining insurance rates.

The seismic hazard studies also may generate two standard measures of anticipated ground motion, both confusingly abbreviated MCE; the simpler probabilistic Maximum Considered Earthquake, used in standard building codes, and the more detailed and deterministic Maximum Credible Earthquake incorporated in the design of larger buildings and civil infrastructure like dams or bridges. It is important to clarify which MCE is being discussed. Calculations for determining seismic hazard were first formulated by C. Allin Cornell in 1968 and, depending on their level of importance and use, can be quite complex.

The regional geology and seismology setting is first examined for sources and patterns of earthquake occurrence, both in depth and at the at the surface from seismometer records; secondly, the impacts from these

sources are assessed relative to local geologic rock and soil types, slope angle and groundwater conditions. Zones of similar potential earthquake shaking are thus determined and drawn on maps.

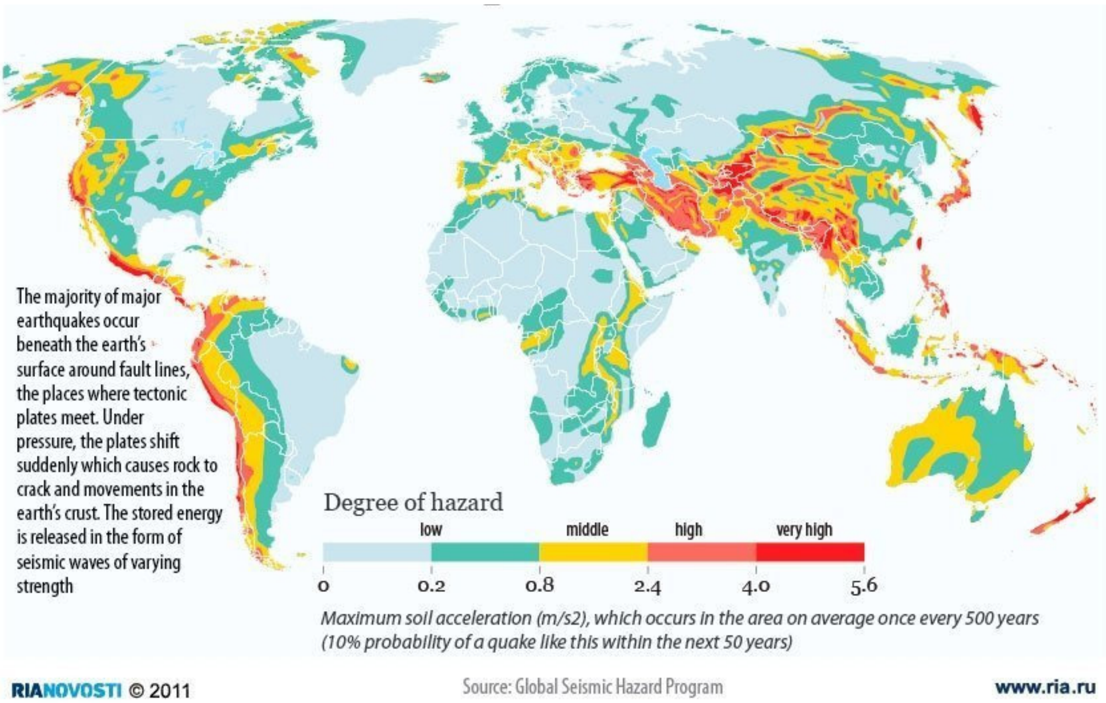

Figure 5.1 Global Seismic Hazard Map [after www.ria.ru]

6. RESULTS:

The definition of a seismic source zone is based - to large extent- on the interpretation of the geological, geophysical and seismological data. Thenhaus (1983) noted that the procedures used in delineating the seismic source zones are ill defined. Seismic zones delineation is important not only for theoretical reasons (improvement of understanding the geodynamics of a region, etc.) but also for practical reasons.

The definition of seismic zones carried out in the present work depends on both of historical and instrumental earthquakes as well as the results of the previous geophysical and geological studies including the kind of seismic faulting [Papazachos et al., 1984], seismicity rate (a-value) [Papazachos, 1980], b values [Hatzidimitriou et al., 1985], major trends of geological zones [Mountrakis et al., 1983], and the fault plane solutions of the major earthquakes (i.e. strike, dip and stress axes). A seismic zone is a configuration within which it is assumed that an earthquake recurrence process is considered to be spatially and temporally homogeneous. The delineation of the seismotectonic sources is usually represents the major part of any seismic hazard analysis.

According to this study the seismic activities are concentrated in four narrow belts (Fig. 6.1) and these belts are: 1) Southern Arabian Shield zone. 2) Southern Red Sea zone. 3) Northern Yemen zone. 4) Middle of Red Sea zone.

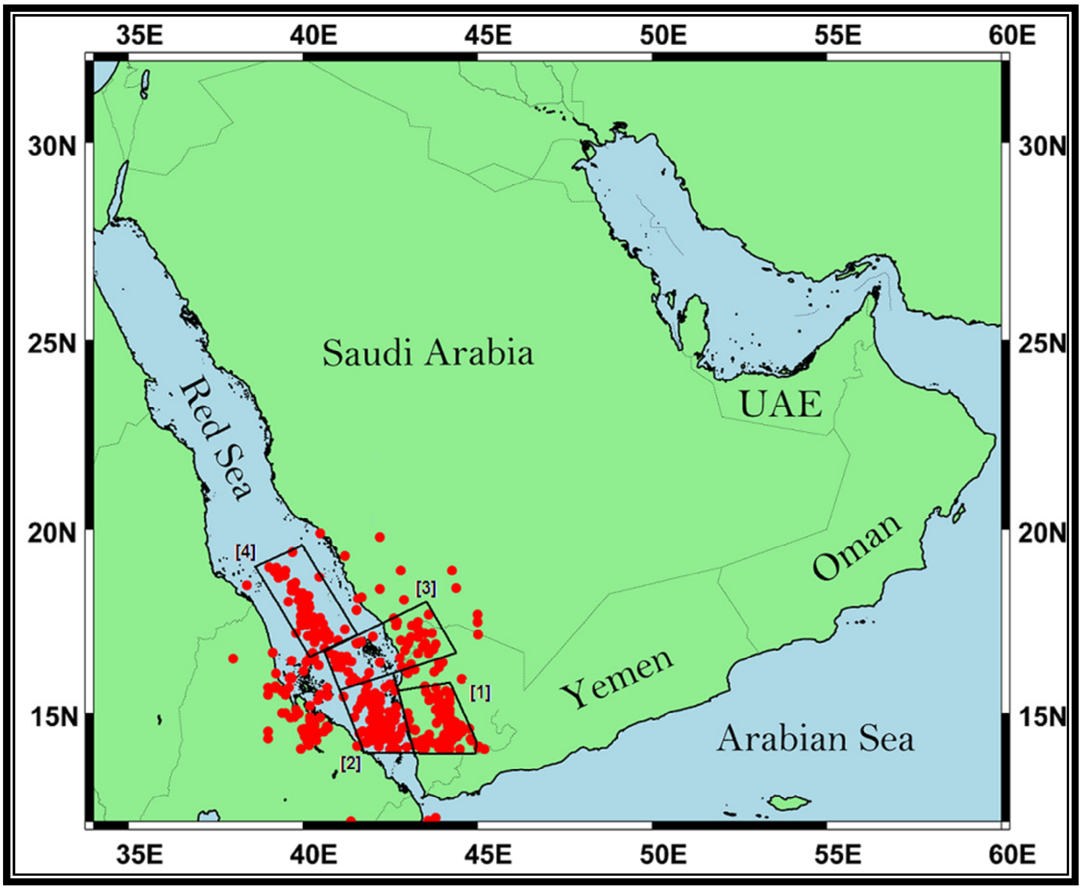

Figure 6.1 Seismic source zones [after, Almalki and Alalmri, 2009]

1- Southern Arabian Shield zone:

This zone includes the Sadah active fault which characterized by its higher seismic activity. The strongest earthquake that occurred in this zone is December 12, 1982 earthquake (M_s = 6.1). The fault plane solution of this earthquake indicates normal fault. There are many destructive earthquakes and swarms have occurred in this zone [Ambraseys, 1988 and Al-Amri 1998].

2- Southern Red Sea zone:

This zone includes many earthquakes occurred in the southern Red Sea and north of Gulf of Aden. This zone characterized by high rate of seismic slip and this due to presence of this zone near to the triple junction point between east African Rift system, Gulf of Aden and the Red Sea. The Heat Flow studies also indicate that there is a high rate of Heat Flow Density (HFD) due to igneous magmatic intrusions in this seismic zone. From the fault plane solution of earthquakes in this zone indicate that about 75% of earthquakes were occurred along the normal faults (Dhamar area) while, 25 % were strike-slip fault (Zabid area).

3- Northern Yemen zone:

This zone includes the earthquakes located in the axial trough and the main trough of the Red Sea. It is noticed that there are two types of faults prominent in the Red Sea; the Red Sea Axial Rift Spreading System of faults and the other is the transform faults. It is concluded that the seismic activity in this zone is related to the transform faults accompanied with the tensional movements. But the seismic activity of this zone in the mainland is related to isolated (not connected) tectonic structures where the strongest earthquake in this zone was in January 11, 1941 (M_s = 6.2).

4- Middle of Red Sea zone:

This zone includes the seismic activity extends along the axial trough of the Red Sea which is characterized by high rate of Heat Flow Density and Bouguer anomalies. The seismic activity in this zone is related to the opening mechanism of the Red Sea (Al-Amri 1994 and 1998). From the earthquakes that occurred in this zone, the 1967 earthquake ($M_b = 6.7$) with strike-slip fault (Fairhead, 1968; Mckenzie et al., 1970; Fairhead and Girdler 1970 and 1972).

7. CONCLUSIONS

This study depends on the available geological, geophysical and seismological data to assess the seismic hazard for the area. The area characterized by complicated geological structures due to the tectonic movements and volcanic eruptions accompanied with the Red Sea and later. This is indicated in the presence of various topographic features in Saudi Arabia and the Northern Yemen. From the distribution of both historical (200–1964) and instrumental (1964-2005) earthquakes, it is noticed that there are more than five hundreds of earthquakes have occurred in the area. Their magnitudes range from $2 \leq M \leq 8.0$. Most of earthquakes are epicentred along the transform faults of the southern Red Sea and southern Arabian Shield. The seismological catalogue is completed for earthquakes with magnitude less than 3 from 2001. About 218 earthquakes have relocated using more recent crustal structure models to enhance their location. Depending on these data there are four seismic source zones have defined for the area and these are; Southern Arabian shield zone; Southern Red Sea zone; Northern Yemen and Middle of Red Sea source zone. The seismic hazard potentialities for the southern Red Sea are relatively high but the presence of the oceanic crust and salt structures may attenuate the seismic waves

BIBLIOGRAPHY

Abdel-Gawad, M., 1969. New evidence of transcurrent movements in the Red Sea area and Petroleum implications, Am. Assoc. Petrol. Geol. Bull., 53, 7, 1466-1479.

Al-Amri A. M., 1994. Seismicity of the south-western region of the Arabian Shield and southern Red Sea, Department of Geology, King Saud University, Journal of African Earth Sciences, Vol. 19, No 1, pp. 17-25.

Al-Amri, A. M., 1995. Preliminary seismic hazard assessment of the southern Red Sea region, European Earthquake Engineering, pp. 33-38.

Al-Amri, A. M., 1998. The crustal structure of the Western Arabian platform from the spectral analysis of long-period P-wave amplitude ratios, Tectonophysics, 290, pp.271-283.

Al-Amri, A. M., Punsalan B. T. And Uy E. A., 1998. Spatial distribution of the seismicity parameter in the Red Sea reigions. Journal of Earth Sciences, Vol. 16, Nos. 5-6, pp. 557-563.

Al-Amri A. and Alkhalifah T., 2004. Improving the level of seismic hazard parameters in Saudi Arabia using earthquake location and magnitude calibration. Project no. 20-68, King Abdul Aziz City for Science & Technology, Riyadh.

lsinawi, S. A., 1986. Historical Seismicity of the Arab Region. Proceedings of the Third Arab Seismological Seminar, Riyadh Saudi Arabia, pp. 11-33.

Ambraseys N. N., 1988. The seismicity of Saudi Arabia and adjacent area, Report Perpared for the Kingdom of Saudi Arabia. ESEE, Imperial Col. Sci. Tech., London, U.K. Report 88/11. 294p

Ambraseys, N. N. and Melville, C.P., 1983. Seismicity of Yemen. Nature, Vol. 303, pp. 321-323.

Ambraseys, N. N.; Melville, C.P. and Adams, R. D., 1994. The Seismicity of Egypt, Arabia and the Red Sea- A historical review. Cambridge University Press and King Abdul Aziz City for Science and Technology, 181p.

Brown, G. F., Jackson, R. O., Bogue, R. G., and Maclean, W. H., 1963. Geologic map of the Southern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geol. Survey Misc. Geol. Inv. Map I-210A, scale 1:500,000.

Drake, C. L. and Girdler, R. W., 1964. A geophysical study of the Red Sea. Royal Astron. Soc. Geophys. Jourl, 8, 473-495.

Fairhead, J. D., 1968. The seismicity of East African rift system 1955-1968, MSc Dissertation, University of Newcastle upon Tyne.

Fairhead, J. D. and Girdler, R., 1970. The seismicity of the Red Sea, Gulf of Aden and Afar triangle, Phis. Trans. R. Soc. Lond. A, 267, pp. 49-74.

Fairhead, J. D. and Girdler, R., 1972. The seismicity of East African rift system, Tectonophysics, 15, pp.115- 122.

Makris, J., Berendsen, D and Denecke, C., 1986. Sonne cruise no. 29 in the central Red Sea. Tech. Rept., Project No. R 341, IfG Hamgurg, 34 p.

Makris, J., Bobsien, M., Meier, K. and Rihm, R., 1989. Sonne cruise no. 53 in the southern Red Sea. Tech. Rept., Project No. R 383 B6, IfG Hamburg, 83 p.

McKenze, D.; Davis D. and Molnar, P., 1970. Plate tectonics of the Red Sea and east Africa. Nature vol. 226, pp. 243-248.

Poirier, J.P. and Taher, M.A., 1980. Historical Seismicity in the Near and Middle East, North Africa and Spain from Arabic Documents (VIIth-Xviith century).Bull. Seism. Soc. Amer. Vol. 70, No. 6, pp. 2185-2201.

Powers, R., Ramierez, L., Redmond, C.& Elberg, E., 1966. Geology of the Arabian Peninsula: Sedimentary geology of Saudi Arabia, US Geol. Surv. Prof. Paper, 560-D, 147 pp.

Reiter, L., 1991. Earthquakes hazard analysis, Colombia Univ. Press, New York.