Seismotectonics & Seismic Zones of the Arabian Peninsula

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INTRODUCTION

The Arabian Peninsula presents several interesting seismological problems. On the west, rifling in the Red Sea has split a large Precambrian Shield. Active rifling is responsible for the geometry of the plate margins in the west, and southwest. To the south, similar rifling running in a more east-west direction through the Gulf of Aden has separated the Arabian Peninsula from Africa. In the northwest, the Gulf of Aqabah forms the southernmost continuation of the Dead Sea transform. The northern and northeastern boundaries of the Arabian Plate are areas of continental collision, with the Arabian Plate colliding with the Persian Plate.

Modern societies and economics depend upon engineered infrastructures supplying externally supplies such as power for their continued successful operation. The supplies and services enable development and growth to proceed and progress. The administration and distribution of the supplies and services are the means by which society operates on a daily basis, and without which the infrastructures of the region would be adversely affected, economically, socially, and politically.

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.

SEISMIC ZONATION

Seismic zonation is the division of geographic region into smaller areas or zones expected to experience the same relative severity of an earthquake hazard (e.g., ground shaking, ground failure, surface faulting, tsunami wave runup, etc.,). The resulting zonation maps provide community policymakers and development.

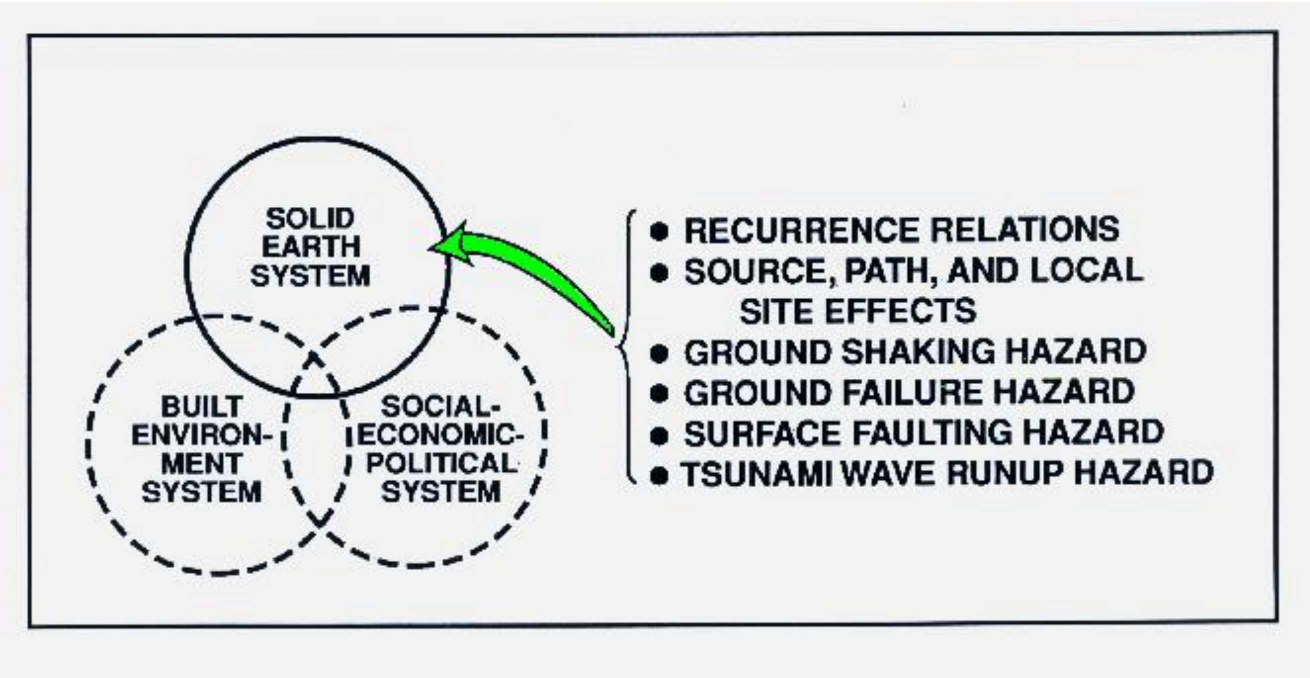
The key questions are summarized below:

1. **Solid Earth System** (i.e., defines the physical characteristics of the source, path, and site which control earthquake hazards (e.g., ground shaking and ground failure hazards)).
   - Where have earthquakes occurred in the past?
   - Where are they occurring now?
   - What is the magnitude and depth distribution of the past and present seismicity?
   - How often have earthquakes of a given magnitude recurred?
   - What are the dominant earthquake generating mechanisms?
   - What levels of ground shaking have occurred in the past? Ground failure? Surface fault rupture? Tsunami wave runup?
   - What are the maximum levels that might be expected in future earthquakes?

2. **Built Environment System**, (I,e., defines the temporal and spatial distribution of buildings and lifeline systems exposed to earthquake hazards).

- What are the physical characteristics of the present inventory of buildings and lifeline systems (e.g., age, type of materials, number of stories, elevation, plan, foundations, etc.)? The future inventory?
- How have these buildings and lifeline systems performed in past earthquakes (e.g., what are the vulnerability relations for each type of building and lifeline?

3. **Social-Economic-Political System**, (I,e., defines the community's earthquake risk management policies and practices (e.g., mitigation, preparedness, emergency response, and recovery).
   - What risk management policies and practices (i.e., building and land use regulations) have been adopted by the community in the past?
   - How have they been enforced?
   - How effective have they been?



REDUCTION OF COMMUNITY VULNERABILITY

BUILT ENVIRONMENT

- Location value, exposure, and vulnerability of buildings and lifelines at risk earthquake physical effects (hazards) which can cause damage, failure, lo function, release of hazardous materials, injuries, and deaths.

HAZARD ENVIRONMENT	POLICY ENVIRONMENT
* Physical effects such as: Ground shaking; liquefaction; landslides; surface fault rupture; tectonic deformation; fires, and flood waves from seiche, tsunami, and dam break generated in an earthquke and the aftershock sequence; each potentially impacting the built environment.	*Social, technical, Aadministrative, political, legal, and economic forces which shape a community's policies and practices for: earthquake risk management (i.e., prevention, itigation, preparedness, prediction and warning, intervention, emergency), public awareness, training, education, and insurance.

REGIONAL TECTONICS

The surface geological and tectonic settings of the Arabian Peninsula consist mainly of :

1) **The Arabian shield in the west and**
2) **The Arabian platform in the east.**
3) **Tertiary volcanism along the Red Sea coast**
4) **Red Sea & Gulf of Aqabah**

1. The Arabian Shield

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. Along this subduction zone, the Afif terrane and Ar Rayn microplate collided that lasted from about 640-620 Ma. (Al-Husseini 2000). The north trending Rayn anticlines and conjugate northwest and northeast fractures and faults may have formed at this time (Figs 1-3).

The Arabian Shield is an ancient land mass with a trapezoidal shape and area of about 770,000 sq. km.(Fig. 1). Its slightly-arched surface is a peneplain sloping very gently toward the north, northeast, and east. The framework of the shield is composed of Precambrian rocks and metamorphosed sedimentary and intruded by granites. The fold-fault pattern of the shield, together with some stratigraphic relationships suggests that the shield have undergone two

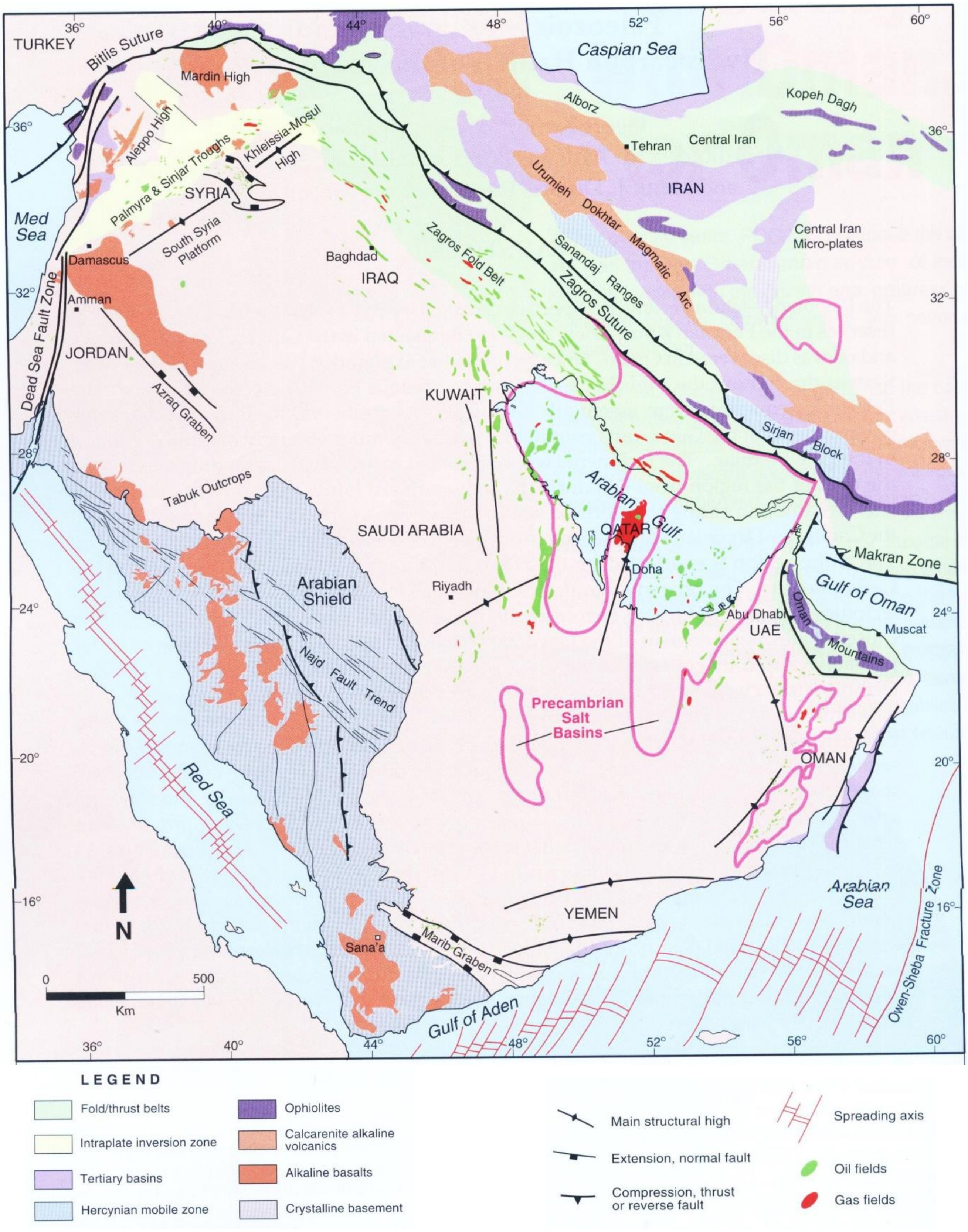


Fig. 1: Location and major tectonic elements of the Arabian plate and Iran. The Makran and Zagros separate the Arabian plate from the microplates of interior Iran.

orogenic cycles. The first cycle was the Al Hijaz orogeny which was more intense and widespread areally. East-west compression was dominant, so that strongly folded and faulted beds of the shield in the west-central part trend northeasterly, while in the southern portion trend generally northerly. The tectonic features include transcurrent, normal and high angle reverse faults, and major fold axes. For the first orogeny, folding and intrusion may have occurred at greater depth. The second cycle was the Al Najd orogeny. This orogeny represents the younger period of mountain building. The effects of the second orogeny were the northwesterly trending left lateral faults. The faults may reflect shearing from shallower movements. The fault systems in this orogeny are subsequent to the other systems and have offset and truncated many of the previous tectonic lineaments. It is one of the most prominent Precambrian Cambrian sinistral wrench fault systems (Chapman 1978).

Following the formation of the Najd fault system, the Arabian shield remained a rather stable platform throughout the Paleozoic and Mesozoic except for several episodes of movement along older faults. The only major orogenic event which affected the region since early Cambrian was the deformation and magmatism associated with the Red Sea rifting. Recently, various speculations have indicated that the Arabian-Nubian shield formed through a process of arc and micro-plate accretion. On the basis of this interpretation, the evolution of the Arabian shield is in terms of 3 stages: (a) magmatic arc; (b) continental collision; (c) intra-cratonic.

To the first order, the Arabian shield is composed of two layers, each about 20km thick, with average velocities of about 6.3 km/s and 7 km/s respectively (Mooney et al 1985). The crust thins rapidly to less than 20 km total thickness at the western shield margin, beyond which the sediments of the Red Sea shelf and coastal plain are underlain by oceanic crust.

2. Arabian Platform

The platform consists of the Paleozoic and Mesozoic sedimentary rocks that unconformably overlays the shield and dip very gently and uniformly to the E-NE towards the Arabian Gulf (Powers et al., 1966). The accumulated sediments in the Arabian platform represent the southeastern part of the vast Middle east basin that extend eastward into Iran, westward into the eastern Mediterranean and northward into Jordan, Iraq and Syria.

The Arabian shield isolated the Arabian platform from the north African Tethys and played an active paleogeographic role through gentle subsidence of its northern and eastern sectors during the Phanerozoic, allowing almost 5000 m of continental and marine sediments deposited over the platform. This accumulation of sediments represents several cycles from the Cambrian onward, now forms a homocline dipping very gently away from the Arabian shield.

Several structural provinces can be identified within the Arabian platform : 1) An interior homocline in the form of a belt, about 400 km wide, in which the sedimentary rocks dip very gently away from the shield outcrops. 2) An interior platform, up to 400 km wide, within which the sedimentary rocks continue to dip regionally away from the shield at low angles. 3) Intra-shelf depressions, found mainly around the interior homocline and interior platform (Fig. 2).

Unfortunately, no locally recorded earthquake data have been used to determine the crustal characteristics of the Arabian platform. 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 (Husseini 2000, Looseveld et al 1996). 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. 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 kilometers. 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.

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

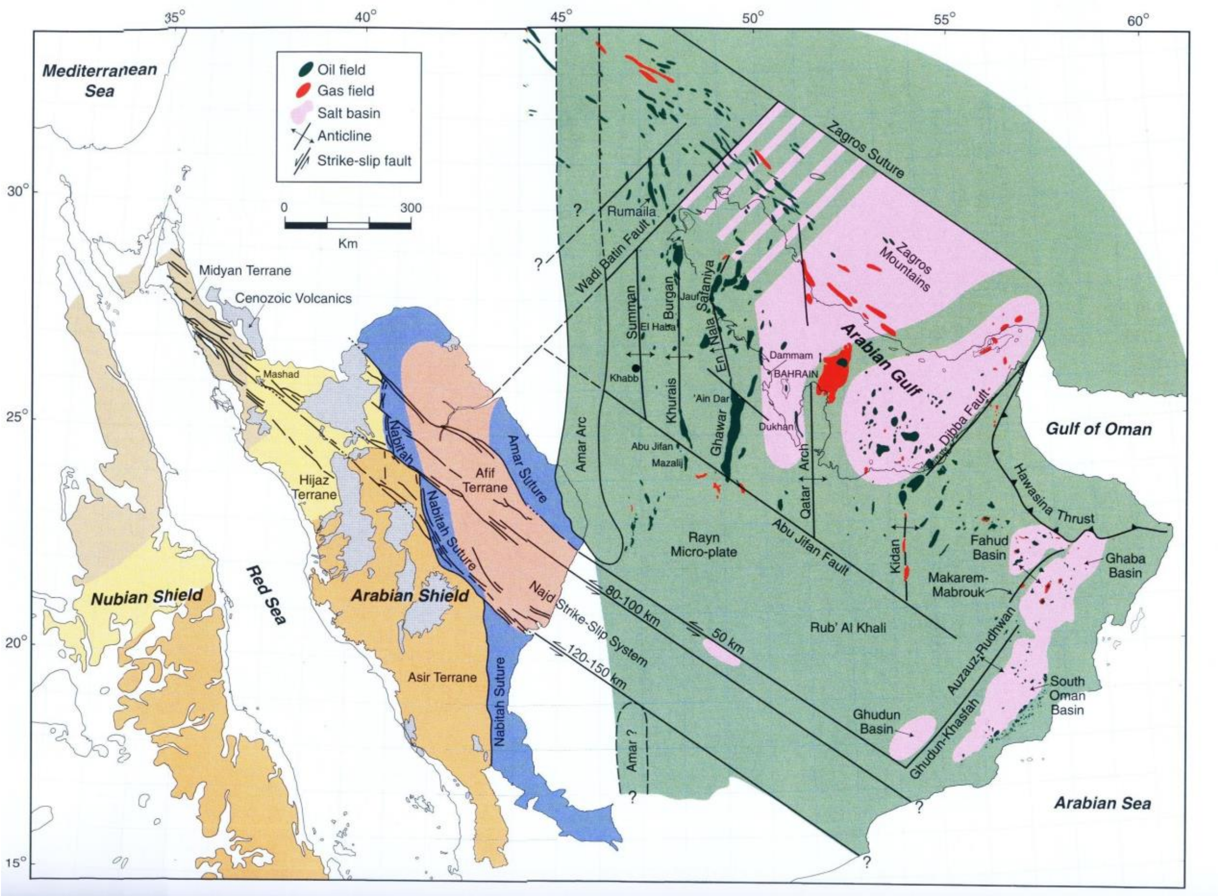


Fig. 2 : The terranes, and Amar Arc of the Rayn micro-plate. The Rayn micro-plate (Green) forms the eastern part of the Arabian Plate (Al-Husseini, 2000).

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 600-540 Ma (Looseveld et al1996, 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 fore-bulge that preceded 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 foredeep develops, a dextral transtension along the Fahud fault zone, and a sinistral transtension 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 & Asharhan 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 (Peters et al 1995). 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.

3. Tertiary Volcanism

Two distinct phases of continental magmatism are evident in western Saudi Arabia. The first phase produced tholeiitic-to-transitional lavas emplaced along NW trends from about 30 to 20 Ma. The second phase produced transitional-to-strongly alkalic lavas emplaced along NS trends about 12 Ma to Recent. The first phase is attributed to passive-mantle upwelling during extension of the Red Sea Basin, whereas the second phase is attributed to active mantle upwelling but was facilitated by minor continental extension perpendicular to plate collision (Camp & Roobol 1989, 1992). The second phase is largely contemporaneous with a major period of crustal uplift to produce the West Arabian swell. The central axis of the uplift and magmatism of the Arabian swell is symmetric and coincides with two fundamental features which are the Ha'il-Ruthbah Arch in the north and the Makkah-Madinah-Nafud volcanic line in the south (Camp & Roobol 1989, 1992). Volcanism was widespread in western Saudi Arabia during the Tertiary Period. The oldest lavas, called the Trap Series rest on Cretaceous clastics in Yemen where these are associated closely with the Rifting of the Red Sea. Northward, thick effusions of basalt and andesite cover vast areas. The effusions have been subdivided on the basis of radioactive dating, and these ranges from Oligocene to Holocene.

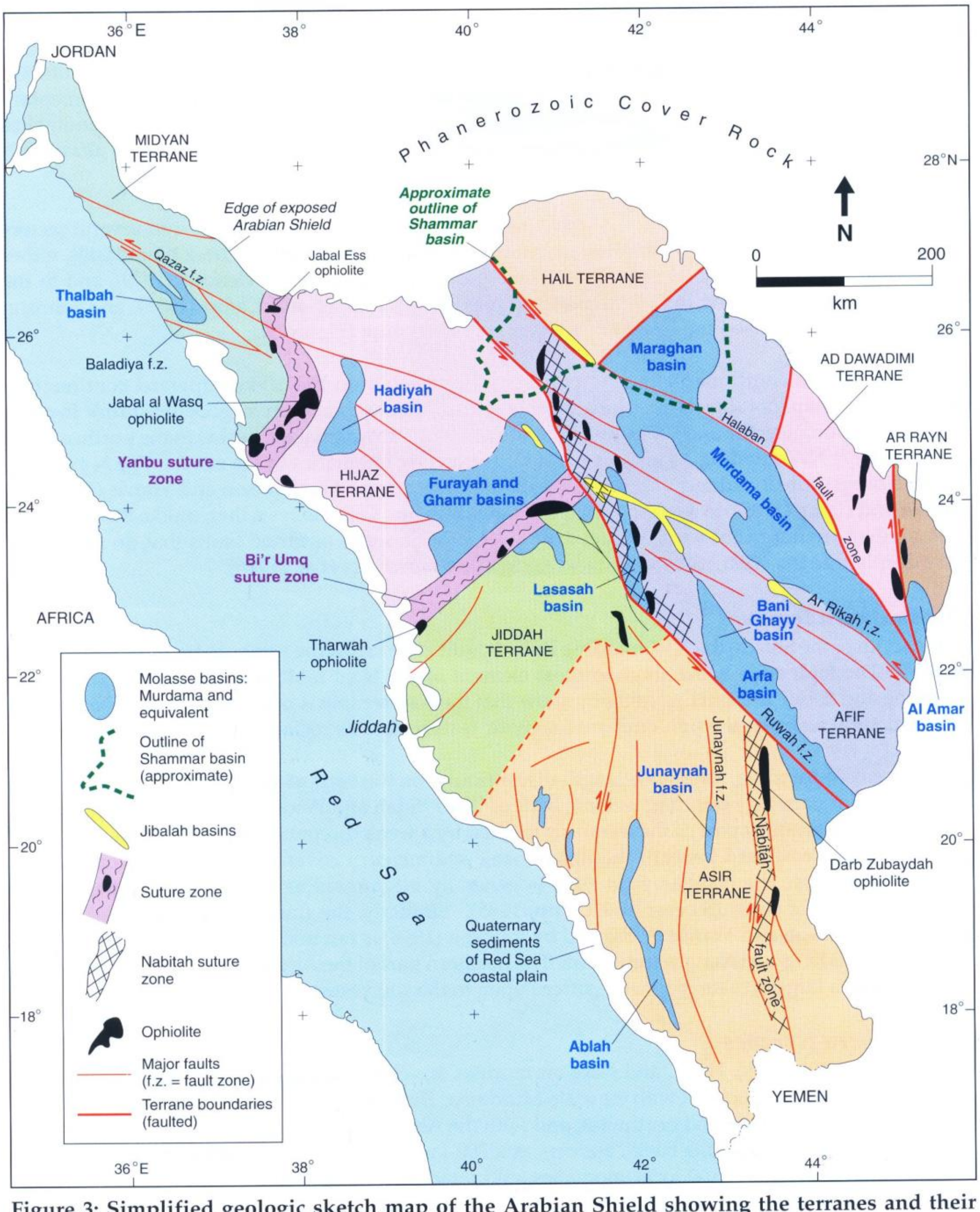


Figure 3: Simplified geologic sketch map of the Arabian Shield showing the terranes and their boundaries, and the main Pan-African structural features and sedimentary basins. Major fault zones, such as Ruwah, Ar Rikah, Halaban, and Qazaz, belong to the Najd fault system.

The Oligocene and Holocene flows were like those of the Trap Series. Thus, volcanism continued up to the present time (Chapman 1978).

4. The Red Sea and Gulf of Aqabah

The Red Sea is an 1800 km elongated trough trending NW-SE from the Sinai Peninsula in the north down to the Strait of Bab Al Mandeb in the south. The Red Sea can be divided into two main physiographic units. These are: (a) the shelf area which is composed of the coastal area and the marginal shelves, (b) the main and axial trough. The shelf is narrow in the north and wide in the south, whereas the trough is wide in the north and narrow in the south.

Structurally, the Red Sea is a graben along the crest of an anticline that formed in the Arabian-African Shield. The inner margins of the shield apparently undergo considerable uplift that formed prominent scarps at the edge of the Red Sea rift. A zone of 1-2 km. wide that is composed of high and tensional faults concealed by coastal sediments lies at the foot of the escarpments. On the seaward side of this zone, the basement has been step faulted downward in blocks and lies beneath the shelf area at depth of 2-3 km below sea level (Chapman 1978).

Three sets of faults seem to have controlled the development of the Red Sea. These were the NW-SE trending main line of faults which are associated with step faulting and the WNW-ESE major fault trend in the Precambrian basement which caused many irregularities in the coastline (Chapman 1978).

The regional distribution of seismicity in the Red Sea indicates concentrated distribution of events proximal to the main and axial trough in the southern portion. However, the concentration is not uniformly distributed, but occurs in clusters on the ridge crests, or near transform faults of the rift axis. Other significant activities appear to occur along other portions of the central rift not having transform faults. The activities may be related to intrusive mechanism, normal fault movements associated with the down dropping of blocks, or movements along undetected transform faults. Focal mechanisms for two earthquakes located near the southern Red Sea rift axis indicate nearly pure strike-slip mechanism on NE trending planes that suggest seismic activity on rift transform faults (Thenhaus et al 1986).

The Gulf of Aqabah forms the southern part of the Levantine transform fault. This fault forms the boundary between the Arabian and African plates. The fault is composed of 4 straight segments (Freund 1970). The first is along the Aqabah and Araba that trends N15E, the second runs along the Dead Sea, Jordan and Hula Valley, the third passes through the Beka'a and Orontes valley, and from Orontes the transform extends up to the Taurus-Zagros thrust. With a total of 105-110km dominant left lateral shear (Quennell 1956; Ben Avraham 1985), minor components of extension, compression and up-warping occur in many places. Normal faults were generated along the margins of the transform due to these systems with variable displacements in the localities of these faults. Changes in the trend of the transform resulted in the formation of rhomb-shaped basins such as the 4 deeps in the gulf and the Dead Sea. On either side of the gulf, long early Neogene dykes trending NW parallel to each other were believed to have accompanied the initial rifting of the Red Sea. This volcanism was followed by the shear along the Gulf of Aqabah. A system of faults sub-parallel to the gulf exists within a zone of tens of kilometers wide on either side. From a study of active faulting in the Dead Sea rift, Garfunkel (1981) indicated that there two types of fault activities. These are the strike-slip and normal, faults, the previous type as the more prominent in activity (El Isa et al 1984).

Seismicity & Crustal Structures

The Arabian Peninsula forms a single tectonic plate, the Arabian Plate. It is surrounded on all sides by active plate boundaries as evidenced by earthquake locations. Figure 4 shows a map of the Arabian Peninsula along with major tectonic features and earthquake locations. Active tectonics of the region is dominated by the collision of the Arabian Plate with the Eurasian Plate along the Zagros and Bitlis Thrust systems, rifting and seafloor spreading in the Red Sea and Gulf of Aden. Strike-slip faulting occurs along the Gulf of Aqabah and Dead Sea Transform fault systems. The great number of earthquakes in the Gulf of Aqabah pose a significant seismic hazard to Saudi Arabia. Large earthquakes in the Zagros Mountains of southern Iran may lead to long-period ground motion in eastern Saudi Arabia.

The two large regions associated with the presence or absence of sedimentary cover define the large-scale geologic structure of the Arabian Peninsula. The Arabian Platform (eastern Arabia) is covered by sediments that thicken toward the Arabian Gulf. The Arabian Shield is has no appreciable sedimentary cover with many outcrops. The Arabian Shield consists of at least five Precambrian terranes separated by suture zones (*Schmidt et al*., 1979). During the late Oligocene and early Miocene, the Arabian Shield was disrupted by the development of the Red Sea and Gulf of Aden rifts, and from the mid-Miocene to the present, the region experienced volcanism and uplift (*Bohannon et al.,* 1989). The uplift and volcanism are generally assumed to be the result of hot, buoyant material in the upper mantle that may have eroded the base of the lithosphere (*Camp and Roobol*, 1992). However details about the nature of the upper mantle, such as its thermal and compositional state, are not known. Volcanic activity (the Harrats) is observed on the Arabian

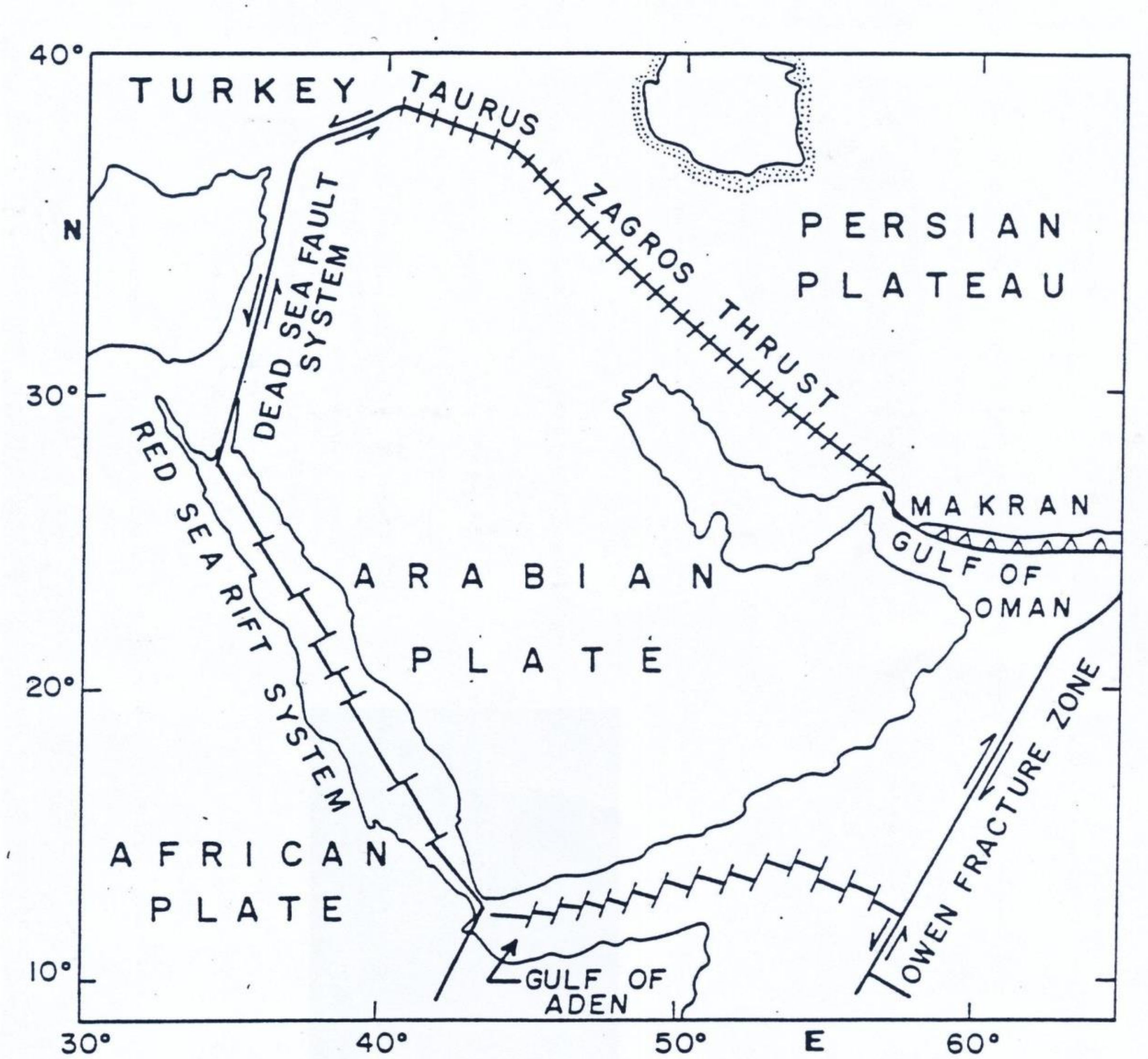


Fig. 4. Plate Boundaries of The Arabian Peninsula

Shield . This is likely to be related to the opening of the Red Sea and mantle asthenospheric upwelling beneath western Arabia (e.g. *Camp and Roobol*, 1992).

The northwestern regions of Saudi Arabia are distinct from the Arabian Shield, as this region is characterized by high seismicity in the Gulf of Aqabah and Dead Sea Rift. Active tectonics in this region is associated with the opening of the northern Red Sea and Gulf of Aqabah as well as a major continental strike-slip plate boundary.

The Dead Sea transform system connects active spreading centers of the Red Sea to the area where the Arabian Plate is converging with Eurasia in southern Turkey. The Gulf of Aqabah in the southern portion of the rift system has experienced left-lateral strike-slip faulting with a 110 km offset since early Tertiary to the present. The seismicity of the Dead Sea transform is characterized by both swarm and mainshock-aftershock types of earthquake activities. The instrumental and historical seismic records indicate a seismic slip rate of 0.15-0.35 cm/year during the last 1000-1500 years, while estimates of the average Pliocene-Pleistocene rate are 0.7-1.0 cm/year.

Previous seismicity studies in the Gulf indicate a relatively lower seismic activity (Ben-Menahem 1981). However, lately there were recent seismic activities that have occurred. These were the 1983 sequence that lasted about 2 months and associated with a maximum magnitude (Mmax) of 5.2. In April 1990 and in May 1991 which have peak Mmax of 4.3 respectively were another 2 set of earthquake sequences that have occurred. These two swarms indicate a spatial overlap with the southern part of the 1983 events, suggesting the 1983, 1990, and 1991swarms were a part of one tectonic segment and activity in the Elat deep. The sequences were followed later by the 1993 event which was located in the Aragonese Deep with Mmax of 5.8. The latest earthquake of concern that is located also in the Aragones Deep is the 1995 event with Mmax of 7.1, which is the strongest among the events that has occurred in the gulf.

Seismicity activities in the Gulf of Aqabah have been dominated by earthquake sequences lasting for about 1-3 months, with a clear pattern of spatial distribution that cover a specific tectonic segment. Each segment is observed to goes through a seismic swarm cycle. Interaction between segments influences the time period of their cycle.

Historically, the most significant earthquakes to hit the Dead Sea region were the events of 1759 (Damascus), 1822 (Aleppo), and of 1837 ;1068 (Gulf of Aqabah area) caused deaths of more than 30,000 people. *Ben Menahem* (1979) indicated that about 26 major earthquakes (6.1<ML<7.3) occurred in southern Dead Sea region between 2100 B.C. and 1900 A.D. In 1980's and 1990's, the occurrence of earthquake swarms in 1983, 1985, 1991, 1993 and 1995 in the Gulf of Aqabah clearly indicates that this segment is one of the most seismically active zones in the Dead Sea transform system. Earthquake locations provide evidence for continuation of faulting regime from the Gulf northeastward inland beneath thick sediments, suggesting that the northern portion of the Gulf is subjected to more severe seismic hazard compared to the southern portion (*Al-Amri et al.*,1991).

Seismic activity in the Arabian shield appears to be low. There were only few moderate seismic events composed of 25 (4.0<Ms<5.9) and 1 (Ms>6.0) to have occurred since 1900. However, historical accounts (Ambraseys 1988) indicated that strong ground shaking has been felt in the northwestern portion of the shield during the 1068 event (Ms7.0) and 1588 event (Ms6.7). The Ms(7.0) was accompanied by ground cracking and fissuring that caused widespread destruction. The central portion was also shaken in the year 1269 which was felt at Taif. This earthquake was associated to the activity of the right lateral NE trending Ad Damm fault which passes close to Taif. In 1256, the City of Madinah also experienced ground shaking. However, the shaking phenomenon was more related to volcanic activity (Fig.5).

In contrast to the scarcity of information regarding earthquakes in the northern and central portion of the shield that has affected the population, a continuous document of felt, strongly felt, and destructive earthquake occurrences in Yemen since the year 742 was compiled by Ambraseys (1988). The location of these earthquake events are primarily distributed in the Yemen Trap Series. The 13 of December 1982 Dhammar earthquake (Ms6.1) killed 2,000 people, destroyed 300 villages, and rendered 700,000 homeless.

To the south, the majority of earthquakes and tectonic activity in the Red Sea region are concentrated along a belt that extends from the central Red Sea region south to Afar and then east through the Gulf of Aden. There is little seismic activity in the northern part of the Red Sea, and only three earthquakes have been recorded north of latitude 25^{o} N. Instrumental seismicity of the northern Red Sea shows that 68 earthquakes ($3.8<mb<6.0$) are reported to have occurred in the period from 1964 to 1993 (Fig. 5).

Historically, about 10 earthquakes have occurred during the period 1913-1994 with surface-wave *(Ms)* magnitudes between 5.2 and 6.1. Some of these events were associated with earthquake swarms, long sequences of shocks and aftershocks (the earthquakes of 1941, 1955, 1967 and 1993). The occurrence of the January 11,1941 earthquake in the northwest of Yemen (*Ms = 5.9*) with an aftershock on February 4, 1941 *(Ms* = 5.2), the earthquake of October 17, 1955 *(Ms* = 4.8), and the 1982 Yemen earthquake of magnitude 6.0 highlight the hazards that may result from nearby seismic sources and demonstrate the vulnerability of northern Yemen to moderate-magnitude and larger earthquakes. Instrumental seismicity of the southern Red Sea shows that 170 earthquakes ($3.0<mb< 6.6$) are reported to have occurred in the period 1965-1994. The historical and instrumental records of strong shaking in the southern Arabian Shield and Yemen (1832; 1845; 1941; 1982 and 1991) indicate that the return period of severe earthquakes which affect the area is about 60 years (*Al-Amri*,1995 b).

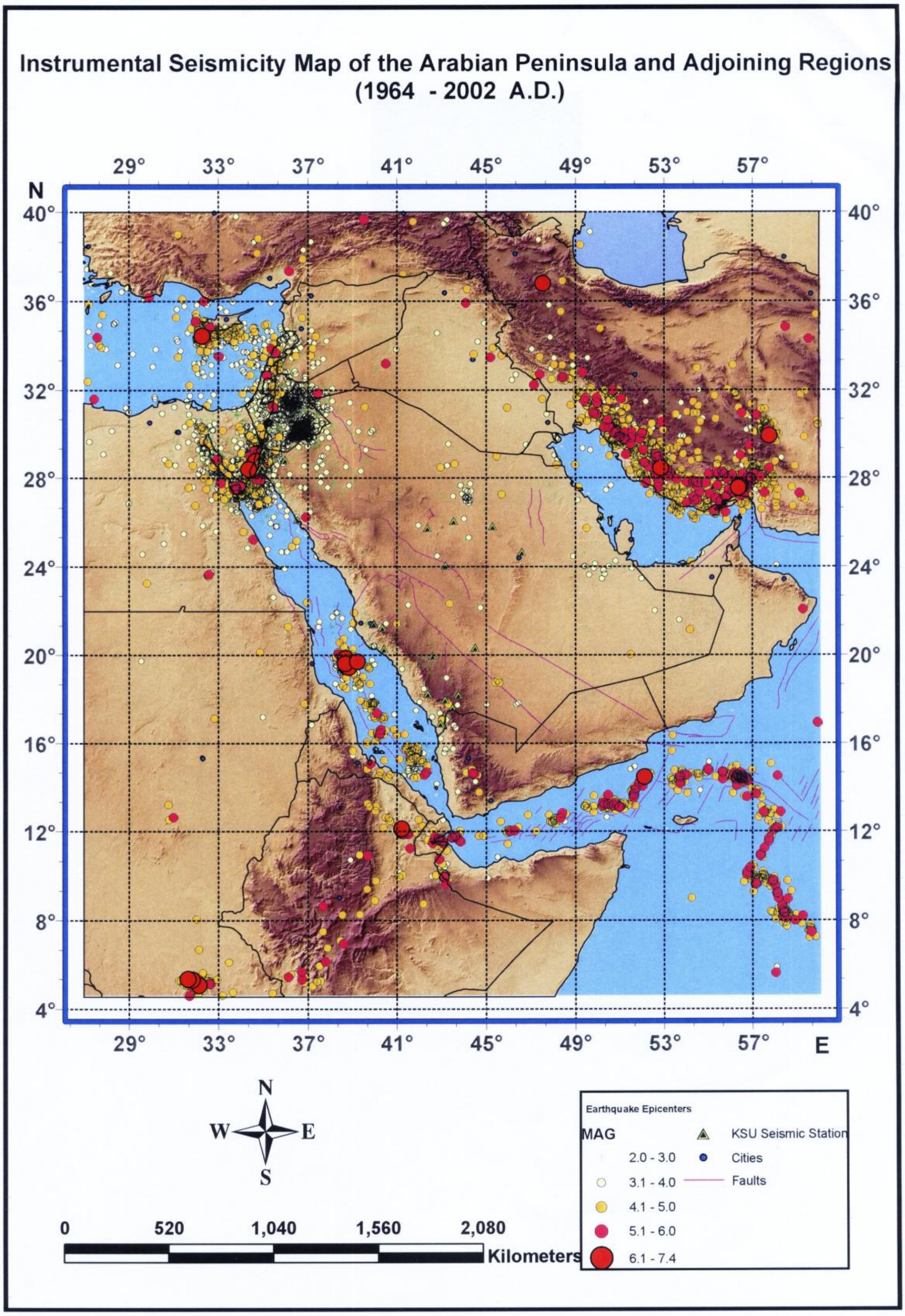


Fig. 5. Seismicity map of the Arabian Peninsula

جدول الزلازل التاريخية والحديثة في شبه الجزيرة العربية التي تم تدوينها وتسجيلها

خلال الفترة من ١١٢ – ٢٠٠٢م

المنطقة	القدر الزلزالي من ٢ –٢,٩٩	القدر الزلزالي من ٣ –٣,٩٩	القدر الزلزالي من ٤ –٤,٩٩	القدر الزلزالي من ٥ –٥,٩٩	القدر الزلزالي أكبر من ٦
خليج العقبة ٣٤–٣٦ شرقاً ٢٨–٣٠ شمالاً	٢٦٩٤	٢٤١٣	٥٥٧	٤١	٥
شمال البحر الأحمر ٣٤–٣٩ شرقاً ٢٤–٢٨ شمالاً	١٩١	٢١٦	٥٢	١٠	٢
وسط البحر الأحمر ٣٥–٤١ شرقاً ١٩–٢٤ شمالاً	٨٦	٧٩	٦٧	٢٦	٦
جنوب البحر الأحمر ٣٧–٤٤ شرقاً ١٢–١٩ شمالاً	١٨٢	٢٠١	١١٠	١٠١	١٥
وسط المملكة ٤٤–٤٨ شرقاً ٢٣–٣٠ شمالاً	٩	١٩	٢	٢	صفر
جنوب الخليج العربي ٤٨–٥٧ شرقاً ٢٣–٣١ شمالاً	١٢	٦٠	٧٣٦	٢٤٣	١٤

The Arabian Plate boundary extends east-northeast from the Afar region through the Gulf of Aden and into the Arabian Sea and Zagros fold belt. The boundary is clearly delineated by teleseismic epicenters, although there are fewer epicenters bounding the eastern third of the Arabian Plate south of Oman. Most seismicity occurs in the crustal part of the Arabian Plate beneath the Zagros folded belt (*Jackson and Fitch*,1981). The Zagros is a prolific source of large magnitude earthquakes with numerous magnitude 7+ events occurring in the last few decades. The overall lack of seismicity in the interior of the Arabian Peninsula suggests that little internal deformation of the Arabian Plate is presently occurring.

The overall lack of seismicity in the interior of the Arabian Peninsula suggests that little internal deformation of the Arabian plate is presently occurring. There is widespread Quaternary volcanism along the Red Sea coast, with at least one documented historical eruption in 1256 A.D. (Barazangi, 1981). Some seismicity was associated with that eruption. Seismicity may also be related to transform faults in the Red Sea continuing onto land as well as other causes. To date, few on-land epicenters are accurately located and there are few focal mechanisms available.

Seismic structure studies of the Arabian Peninsula have been varied, with dense coverage along the 1978 refraction survey and little or no coverage of the aseismic regions, such as the Empty Quarter. In 1978, the Directorate General of Mineral Resources of Saudi Arabia and the U.S. Geologic Survey conducted a seismic refraction survey aimed a determining the structure of the crust and upper mantle. This survey was conducted primarily in the Arabian Shield along a line from the Red Sea to Riyadh. Reports of crust structure found a relatively fast velocity crust with thickness of 38-43 km (*Mooney et al*,1985; *Mechie et al*,1986; *Gettings et al*,1986, *Badri*,1991). The crust in the western shield is slightly thinner than that in the eastern shield.

Mooney et al.(1985) Suggest that the geology and velocity structure of the Shield can be explained by a model in which the Shield developed in the Precambrian by suturing of island arcs. They interpret the boundary between the eastern shield and the Arabian Platform as a suture zone between crustal blocks of differing composition.

Surface waves observed at the long-period analog stations RYD (Riyadh), SHI (Shiraz, Iran), TAB (Tabriz, Iran), HLW (Helwan, Egypt), AAE (Addis-Ababa, Ethiopia) and JER (Jerusalem) were used to estimate crustal and upper mantle structure (*Seber and Mitchell*, 1992; *Mokhtar and Al-Saeed*,1994). These studies reported faster crustal velocities for the Arabian Shield and slower velocities for the Arabian Platform.

The Saudi Arabian Broadband Deployment (*Vernon and Berger et al*., 1997; *Al-Amri et al.,* 1999) provided the first data set of broadband recordings of this region. This deployment consisted of 9 broadband three-component seismic stations along a similar transect an early seismic refraction study (*Mooney et al., 1985; Gettings et al.,1986; Mechie et al.,*1986). Data from the experiment resulted in several studies andd models (*Sandvol et al.,* 1998; *Mellors et al.,* 1999; *Rodgers et al.,* 1999; *Benoit et al.,* 2002). These studies provided new constraints on crustal and upper mantle structure. 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. 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).

Generally the crustal thickness in the Arabian Shield area varies from 35 to 40 km in the west adjacent to the Red Sea to 45 km in central Arabia (*Sandvol et al.*, 1998; *Rodgers et al.,* 1999). Not surprising the crust thins nears the Red Sea (*Mooney et al.,*1985; *Gettings et al.,*1986; *Mechie et al.,*1986). High-frequency regional S-wave phases are quite different for paths sampling the Arabian Shield than those sampling the Arabian Platform (*Mellors et al.,* 1999; *Sandvol et al.,*1998). In particular the mantle Sn phase is nearly absent for paths crossing parts of the Arabian Shield, while the crustal Lg phase is extremely large amplitude. This may result from an elastic propagation effect or extremely high mantle attenuation and low crustal attenuation occurring simultaneously, or a combination of both.

Previous reports of large scale seismic structure (e.g. *Ritsema et al.,*1999 and *Debayle et al.,*2001) suggest that a low velocity anomaly in the upper mantle extends laterally beneath the Arabian Shield from the Red Sea in the west to the shield – platform boundary in the east. Additionally, *Debayle et al*. (2001) observe a narrow region of low velocity beneath the Red Sea and western edge of the Arabian Shield, extending to 650 km depth. A recent tomographic velocity model and receiver function analysis by *Benoit et al.* (2002) suggests the upper mantle low velocity anomaly is smaller in extent, laterally and vertically, than imaged in previous studies.

In order to select a single velocity model to be representative of the paths sampled in the Arabian Peninsula, Alamri and Alkhalifah (2004) made use of the results of a seismic refraction (*Ginzburg et al*., 1979) and a recent composite model of crustal thickness (*Seber et al*., 1997). Their grid search results with the thicker crusts (28-30 km) are consistent with these earlier studies. A grid search was also used to quickly find a range of models that satisfactorily fit the dispersion data, then that range of models was explored to fit the three-component broadband (10-100 seconds) waveforms. The resulting models revealed significant differences between the lithospheric structure of the three regions. The resulting models are plotted in tables 1, 2 and 3 (Al-Amri and Alkhalifah, 2004).

Table 1. Preferred Velocity Model for the Gulf of Aqabah/Dead Sea Region

DEPTH (KM)	THICKNESS(KM)	V_P (KM/S)	V_S (KM/S)
0	2	4.50	2.60
2	5	5.50	3.18
7	10	6.10	3.52
17	11	6.20	3.60
28	∞	7.80	4.37

V_P and V_S are the P- and S-wave velocities, respectively.

Table 2. Preferred Velocity Model for the Arabian Shield Region

DEPTH (KM)	THICKNESS(KM)	V_P (KM/S)	V_S (KM/S)
0	1	4.0	2.31
1	15	6.20	3.58
16	20	6.80	3.93
36	∞	7.90	4.30

V_P and V_S are the P- and S-wave velocities, respectively.

Table 3. Preferred Velocity Model for the Arabian Platform Region

DEPTH (KM)	THICKNESS(KM)	V_P (KM/S)	V_S (KM/S)
0	4	4.00	2.31
4	16	6.20	3.64
20	20	6.4	3.70
40	∞	8.10	4.55

V_P and V_S are the P- and S-wave velocities, respectively.

Identification and Delineation of Seismic Zones

In the identification and delineation of seismic source zones for western Saudi Arabia, some criteria were followed and utilized as guidelines. The criteria are:

1. Seismological parameters- map of the planar distribution of earthquake epicenters (fig. 5) that could indicates both seismogenic provinces and seismoactive faults, and occurrence. Of large earthquakes, the level of which depends upon on the seismic activity in the region. When required and necessary, the magnitudes can be converted to energy values to show the energy flux distribution for better correlation. This procedure can also be applied to the parameter intensity by means of an appropriate conversion relation or conversely a distribution map of the observed maximum intensities in the region. Historical earthquakes are described mostly in terms of intensity and it would seem appropriate to use this parameter as an additional guide. In using the spatial distribution of epicenters as a guideline, boundaries of zones are drawn in such a way that a cluster or more clusters of earthquakes are included and crossed the region of minimum density of epicenters, but do not intersect the main tectonic provinces. The scatter of few seismic data over a wider area could lead to the formation of a seismic source zone with one event, provided the magnitude level is high compared to the level of background seismicity in the region. In principle, this system of clustering can also be applied to energy or intensity distribution to draw the boundary lines that encloses a particular seismic zone same as with the denseness of the epicenters of earthquake events.

2. Geological parameters- map of regional tectonics in the area (figs.1-3) which indicates the location of joints, faults, lineaments and rift systems that are associated with seismic activities. Fracture dislocations are the sources of seismic events. Seismogenic source zones are selected that are composed of a system of faults or lineaments or rift zones whose boundaries do not traverse generally other tectonic units.

3. Geophysical parameters- maps of heat flow and gravity anomaly distributions are useful in the interpretation on the nature of geologic structures. As can be seen on the two maps, there were gradual and distinct changes on the contours shapes and values. The contours shapes and spacing seemed to be consistent with the tectonic locations and orientations in the region. Seismic source zones boundaries are therefore drawn on these distinct or gradual changes.

The boundaries were the results in the inter-agreement of the 3 criteria, with the higher priority given to the spatial distribution of the earthquake epicenters due to statistical needs in seismicity investigation. Likewise, it is observed that some earthquakes cannot be connected to some line sources.

From these considerations, there were twenty five (25) identified and delineated seismogenic source zones for Saudi Arabia (fig. 6 and table 1). The seismogenic source zones are as follows:

Table 1. Seismogenic Source Zones of The Arabian Peninsula

Zone No.	Name	Cooridinates		Area (KM^2)
		Lat. N	Long. E	
1	Gulf of Suez	30.28	31.23	32058
		31.27	32.22	
		27.14	33.87	
		27.81	34.70	
2	Gulf of Aqabah-Dead Sea	32.31	35.22	43050
		32.28	36.48	
		28.33	33.30	
		27.81	34.73	
		28.81	34.02	
3	Tabuk	32.28	36.48	85032
		29.33	35.62	
		28.29	39.75	
		26.35	37.73	
4	Northwestern Volcanic Zone	26.35	37.73	98618
		22.36	40.81	
		23.33	41.72	
		28.29	39.75	
5	Midyan-Hijaz	28.33	35..30	36638
		29.33	35.62	
		21.72	40.24	
		22.36	40.81	
6	Duba-Wajh Area	28.33	35.30	67476
		26.62	33.25	
		23.82	35.74	
		25.62	37.58	
7	Yanbu	23.82	35.74	49614

Zone No.	Name	Cooridinates		Area (KM^2)
		Lat. N	Long. E	
		25.62	37.58	
		21.34	37.22	
		23.37	39.26	
8	Southern Red Sea-Jeddah	21.34	37.22	78009
		23.37	39.26	
		18.20	38.82	
		19.58	41.42	
9	Makkah Region	21.72	40.24	44958
		23.33	41.72	
		18.83	41.84	
		20.62	43.35	
10	Southern Red Sea-Al Darb	18.20	38.82	112358
		19.58	41.42	
		15.88	43.44	
		12.65	42.98	
11	Abha-Jizan	18.83	41.84	44958
		20.62	43.35	
		15.88	43.44	
		17.32	45.27	
12	Southwestern Arabian Shield	15.88	43.44	67323
		12.65	42.98	
		17.32	45.27	
		13.66	46.18	
13	Gulf of Aden	12.65	42.98	335851
		10.37	44.23	
		16.12	54	
		14.05	54.61	

Zone No.	Name	Cooridinates		Area (KM²)
		Lat. N	Long. E	
14	Sirhan-Turayf-Widyan Basins	32.28	36.48	343516
		32.01	47.13	
		26.46	41.72	
		28.29	39.75	
15	Najd Fault Zone	28.29	39.5.75	379730
		20.62	48.36	
		17.32	45.27	
		20.2	43.1	
		23.33	41.75	
16	Central Arabian Graben Zone	26.46	41.72	533174
		30.86	46.02	
		23.52	51.46	
		20..62	48.36	
17	Arabian Gulf	30.86	46.02	257798
		32.01	47.13	
		25.96	54.17	
		23.52	51.46	
18	Zagros Fold Belt	32.01	47.13	160644
		32.01	50.11	
		27.31	55.6	
		25.96	54.17	
19	Sanandaj-Sirjan Ranges	32.01	50.11	148636
		32.0	53.84	
		28.8	57.3	
		27.31	55.6	
20	Southern Yemen	17.32	45.27	408636
		20.62	48.36	
		16.12	54.0	

Zone No.	Name	Cooridinates		Area (KM^2)
		Lat. N	Long. E	
		13.66	46.18	
21	Rub Al Khali-Ghudun Basins	20.62	48.36	403580
		24.16	52.22	
		19.69	57.32	
		16.12	54.0	
		18.02	55.62	
22	Bandar Abbas-Dibba Region	24.16	52.22	140096
		28.8	57.3	
		27.5	58.48	
		22.85	53.76	
23	Makran-Hawasina Thrust Zone	22.85	53.76	324060
		27.5	58.48	
		24.88	61.68	
		19.69	57.32	
24	East Sheba Ridge	16.12	54.0	209585
		18.02	55.62	
		14.09	59.46	
		11.99	57.44	
		14.05	54.61	
25	Masirah Fault Zone	18.02	55.62	238136
		24.88	61.68	
		14.09	59.46	
		19.69	57.34	

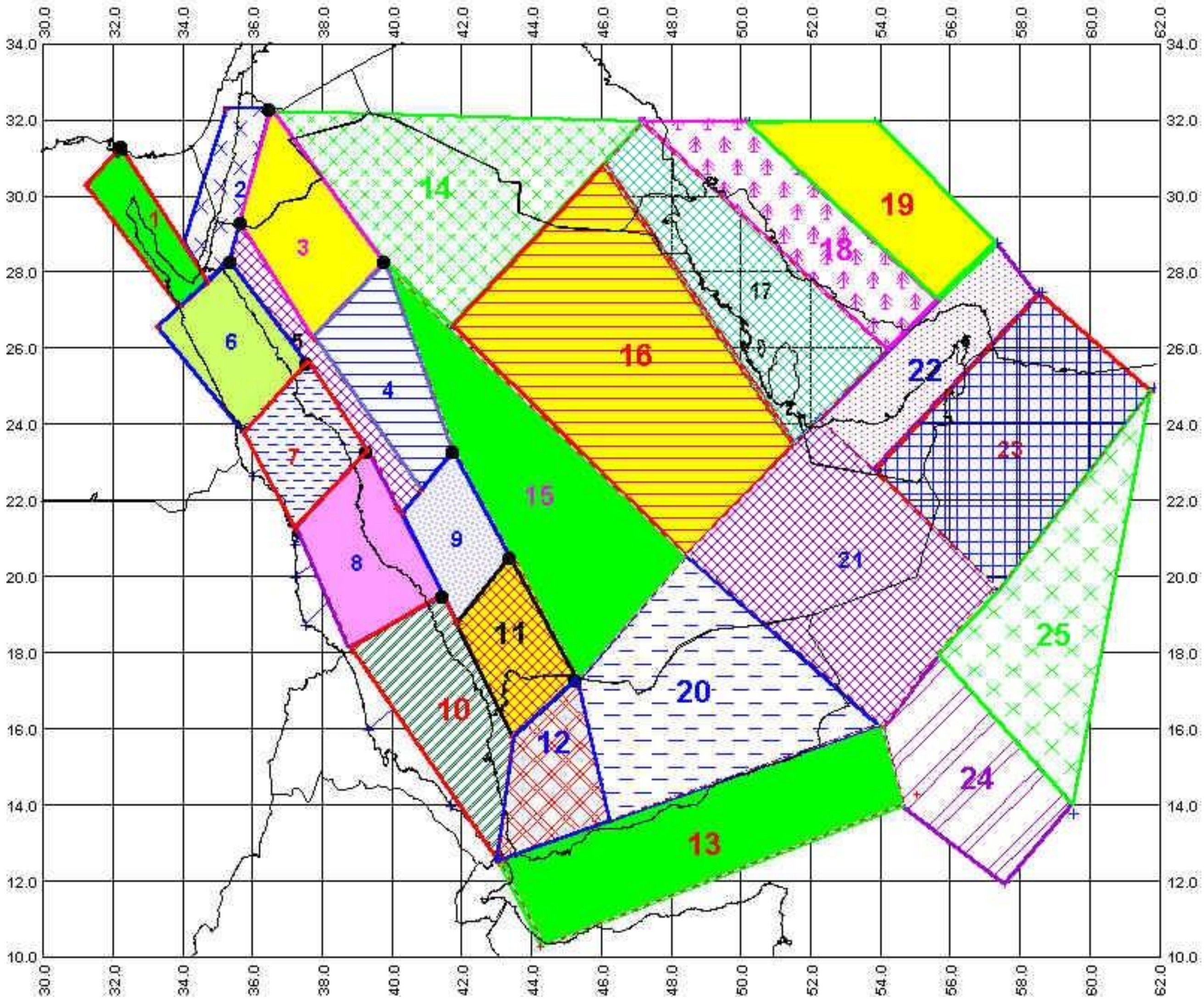


Figure 6. Seismic Source Zones of the Arabian Peninsula and Adjoining Regions

Characterization of Seismic Zones

1. Data Sources and Periods of Observation

In the statistical characterization scheme for the seismogenic source zones in the Arabian Peninsula, different set of seismic data for 2 observation period were compiled and analyzed. The set of observation period were as follows:

(a) Historical period : 112 – 1964 AD

(b) Instrumental Period : 1965- 2003 AD

The main seismic data sources for the 2 period of seismic observation were the seismological catalogues from USGS (PDE/EDR : 1963-2003), IPRG (1927-1999), and Ambraseys (112-1992 AD). These data sources were merged together to give the main database for statistical analysis for the seismicity parameters and related topics. A counter-checking of all the relevant data entries in the catalogues was undertaken to ensure non-duplication of the same earthquake events. For each seismic zone, the minimum magnitude value is 4.0 for all the set of observation period. Under (a), the magnitude type is the surface wave (Ms), while for (b) and (c) is the body-wave (mb) that were used respectively in the seismic analysis. These are due to the reasons that the bulk of seismic data is Ms in (a) and mb in (b) and (c).

Different types of magnitude occur in the seismological catalogues which include intensity data from historical events. To have complete, homogenous, and consistent database, there was a need for converting one type of magnitude to the other types or other seismic parameters. The utilized conversion equations were:

$$Ms = 0.53\ Io + 2 \qquad (1)$$

$$mb = 0.46\ Io + 2.53 \qquad (2)$$

$$mb = 0.87\ Ms + 0.79 \qquad (3)$$

where Io is the epicentral intensity in the MSK intensity scale and the other parameters were as defined formerly. The above empirical relations were taken from Al-Amri et al. (1998). It is assumed that the local magnitude (Ml) is equivalent to Ms. The duration/coda magnitude is the same as mb. These two types of magnitudes (Ms, mb) are presumed to be generally the respective standard values as bases in the determination of the empirical relations for Ml and Md used by some seismological agencies in the EMR.

2. Seismicity Parameters

The compiled seismic data in each seismogenic source zone in each observation period were analyzed to obtain the respective values of the seismicity parameters a and b. The cumulative frequency-magnitude relation

Log N (M) = a – bM **(4)**

was applied in the determination of the seismicity parameters in each source zone. M is the magnitude, N is the total number of events equal and larger than M, a is the seismicity index parameter, and b is the parameter related to the applied stress. This relation (4) was utilized due to the following reasons:

(a) there were zero number of events in some magnitude intervals

(b) the cumulative number of events is directly given by the observed data.

The analysis performed and conducted in each seismic source zone using (4) is carried out into magnitude intervals of increasing increment of 0.1 magnitude unit starting from 0.1 up to 0.5. From these analyses, the best fit was selected as the most representative cumulative frequency-magnitude relation for each observation period in each seismogenic source zone.

There is no fast and hard rule in eliminating foreshocks, aftershocks, and swarm type of earthquake events from the normal background seismicity of an area. Aside from review of the seismic data, the second approach is to remove the excess number of events that deviate from the general linearity of (4) to diminish the influence of the other type earthquake regime. The omission of aftershocks resulted in the decrease of b by amounts smaller than 0.1. This value falls within the range of standard deviations or differences caused by working procedures (Karnirk 1969). A more substantial influence cannot be excluded when strong shallow earthquakes are followed by numerous aftershocks and the period of investigation coincides with such sequence.

In the majority of cases for the seismogenic source zones with sufficient data, the distribution of representative values of Log N(M) plotted for equal magnitude classes fits a straight line fairly well within a certain range of magnitude. A steeper change of slope is observed to occur within the higher magnitude classes and lower slopes for the lower magnitude classes. The earthquakes whose magnitude values fall in the non-linear part are called characteristic earthquakes of the region. Such a pattern is often observed in regions of moderate seismicity as observed in some of the selected seismogenic source zones in the region, where return periods of the large earthquakes exceed the period of observation.

Calculations for the seismicity parameters were undertaken in each observation period in each seismic source when the number of data are equal to 9 and above. It is shown by Aki (1965), that for smaller number of events, the upper and lower confidence limit for the b value is large even with small probability. Although the minimum number of events that can be used in calculation of the seismicity parameters is 4, the validity of the results are uncertain (Welkner 1967).

(3) Maximum Magnitude

It should be noted that the hypothesis of linearity in (4) is correct only if the considered magnitude interval is not too large. It is also clear that this may end to unrealistic results the extrapolation of (4) in magnitude ranges outside the observed data. This is mainly due to the absence of a limiting value for M, while it is evident that such limits must exist due to physical consideration. Hence, (4) is supposed to be valid only for magnitude less than or equal to a limiting value Mt, giving Log N(M) =0 when M> Mt (truncated distribution). An upper magnitude limit has to be defined, chosen as Mmax = (a/b) where a and b are the constants in (4). This Mmax refers only to the limited data upon which (4) is regressed. Mmax is not the absolute maximum magnitude, but only relative to the utilized data.

Modeling of Seismic Zones

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 the Arabian Peninsula were based on the following empirical and theoretical correlations. The empirical correlation was taken from observation of earthquakes occurring in tectonic structures (Gubin 1967; Allen 1975). These are as follows:

1. 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 sronger 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.

2. Correlation between Earthquake Frequency and Mechanics of Faulting

The geological interpretation of the mechanism of an earthquake could possibly have started by Lawson in 1908, which was translated by Reid (1910) into quantitative terms (Lomnitz 1987). The concept established 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 & Richards 1980; Burridge & Knopoff 1964; Keilis Borok 1959)

Mo = uAD = uLWD (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 world-wide data collection of corresponding magnitude, moment, length, width and displacement. The empirical relationships that were obtained are as follows:

Log Mo = [(1.62+-0.112)Ms + 15.1] +-0.3 (2)

Log Mo = [(2.54+-0.087)Log L + 22.56] +-0.31 (3)

Log Mo = [(2.61+-0.28)Log D +26.32] +-0.44 (4)

From (2-4), the following equations can be obtained when the standard deviation and standard error of estimate are not incorporated

Log L = 0.64Ms – 2.94 (5)

Log D = 0.62Ms – 4.3 (6)

Equation (2) is within the range of values (1.5-1.7) as obtained by Kanamori (1977), Hanks & Kanamori 1979; Brune 1968; Scholz 1982; Wyss and Brune (1968), and others. Equations (5) and (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 (2-4)

1.52LogD + 7.25 < Ms < 1.69LogD + 6.65 (7)

1.55LogL + 4.36 < Ms < 1.6LogL + 4.94 (8)

The magnitude frequency relation of earthquakes satisfies the empirical relation (Gutenberg

& Richter 1954)

$$\text{Log } N = a - bMs \qquad (9)$$

where N is the number of magnitude Ms or greater, a and b the seismicity parameters. Equation (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 (9) can be expressed in terms of Mo by means of (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 (2) and (9), a power law size distribution of earthquakes can be obtained (Wyss 1973)

$$N(Mo) = Amo^{(-B)} \qquad (10)$$

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

$$B = b/d$$

where a and b, c and d are the constant and coefficient in (9) and (2) respectively. From Wyss (1973), the total moment of a given earthquake population is the integral

$$Mo(tot) = (AB/(1-B)[Mo^{(1-B)}] \qquad (11)$$

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 (10) it is assumed that the Mo(max) is attained when N(Mo)=1, so that $A=Mo^B$. Likewise, in (9) the Mmax is also attained when N(M) =1. If Mo(min) is insignificant compared to Mo(max), (11) becomes approximately equal to

$$Mo(tot)= B/(1-B)Mo(max) \qquad (12)$$

From Wesnousky et al (1983), the repeat time (Tmax) of (11) is

T(max) = Mo(tot)/Mo(g) (13)

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

In (6), the recurrence time (Tmax) of an event with dislocation D is

T(max) = D/S (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 (9-14) 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 1998; Al-Amri 1994)

Ms = 1.14 Mb -0.9 (15)

where Mb is the body-wave magnitude.

Wesnousky (1986) had 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 (12).

The expected maximum magnitude in each seismogenic source zone is either taken from (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 [Mmax(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 (5) or dislocation in (6), and the magnitude from crustal depth (H) which is given as

$$\mathbf{Mmax(H) = 4Log\ H + 1.8} \qquad \mathbf{(16)}$$

The corresponding feasibilities in (5), (6), (9) and (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

$$\mathbf{Pr = 1\text{-}exp(\text{-}t/Tmax)} \qquad \mathbf{(17)}$$

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 (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.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..

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Earthquake Glossary

acceleration. When you step on the accelerator in the car or put on the brakes, the car goes faster or slower. When it is changing from one speed to another, it is accelerating (faster) or decelerating (slower). This change from one speed, or velocity, to another is called acceleration. During an earthquake when the ground is shaking, it also experiences acceleration.

active fault. A fault that is likely to have another earthquake sometime in the future. Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years.

aftershocks. Earthquakes that follow the largest shock of an earthquake sequence. They are smaller than the mainshock and within 1-2 fault lengths distance from the mainshock fault. Aftershocks can continue over a period of weeks, months, or years. In general, the larger the mainshock, the larger and more numerous the aftershocks, and the longer they will continue.

amplification. Most earthquakes are relatively small, in fact, so small that no one feels them. In order for seismologists to see the recording of the movement of the ground from the smaller earthquakes, the recording has to be made larger. It's like looking at the recording through a magnifying glass, and the amount that it is magnified is the amplification. Shaking levels at a site may also be increased by focusing of seismic energy caused by the geometry of the sediment velocity structure, such as basin subsurface topography, or by surface topography.

attenuation. When you throw a pebble in a pond, it makes waves on the surface that move out from the place where the pebble entered the water. The waves are largest where they are formed and gradually get smaller as they move away. This decrease in size, or amplitude, of the waves is called attenuation.

creep. Slow, more or less continuous movement occurring on faults due to ongoing tectonic deformation. Faults that are creeping do not tend to have large earthquakes.

displacement. The difference between the initial position of a reference point and any later position. The amount any point affected by an earthquake has moved from where it was before the earthquake.

earthquake. This term is used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth.

earthquake hazard. Anything associated with an earthquake that may affect the normal activities of people. This includes surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunamis, and seiches.

earthquake risk. The probable building damage, and number of people that are expected to be hurt or killed if a likely earthquake on a particular fault occurs. Earthquake risk and earthquake hazard are occasionally used interchangeably.

epicenter. The point on the earth's surface vertically above the point in the crust where a seismic rupture begins.

fault. A fracture along which the blocks of crust on either side have moved relative to one another parallel to the fracture. **Strike-slip faults** are vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral. **Dip-slip faults** are inclined fractures where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed **normal**, whereas if the rock above the fault moves up, the fault is termed **reverse (or thrust)**. Oblique-slip faults have significant components of both slip styles.

foreshocks. Foreshocks are relatively smaller earthquakes that precede the largest earthquake in a series, which is termed the mainshock. Not all mainshocks have foreshocks.

ground failure. A general reference to landslides, liquefaction, lateral spreads, and any other consequence of shaking that affects the stability of the ground.

ground motion (shaking). The movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface.

intensity. A number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several scales exist, but the ones most commonly used in the United States are the Modified Mercalli scale and the Rossi-Forel scale. There are many intensities for an earthquake, depending on where you are, unlike the magnitude, which is one number for each earthquake.

landslide. The downslope movement of soil and/or rock.

liquefaction. A process by which water-saturated sediment temporarily loses strength and acts as a fluid, like when you wiggle your toes in the wet sand near the water at the beach. This effect can be caused by earthquake shaking.

magnitude. A number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (ML), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (Ms), (3) body-wave magnitude (Mb), and (4) moment magnitude (Mw). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (Mw) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales should yield approximately the same value for any given earthquake.

mainshock. The largest earthquake in a sequence, sometimes preceded by one or more foreshocks, and almost always followed by many aftershocks.

microzonation. The identification of separate individual areas having different potentials for hazardous earthquake effects.

percent "g". G or g is the force of gravity. When there is an earthquake, the forces caused by the shaking can be measured as a percentage of the force of gravity, or percent g.

Poisson distribution. A probability distribution that characterizes discrete events occurring independently of one another in time.

recurrence interval. The average time span between large earthquakes at a particular site. Also termed return period.

seismic gap. A section of a fault that has produced earthquakes in the past but is now quiet. For some seismic gaps, no earthquakes have been observed historically, but it is believed that the fault segment is capable of producing earthquakes on some other basis, such as plate-motion information or strain measurements.

seismic zone. An area of seismicity probably sharing a common cause. Example: "The New Madrid Seismic Zone."

shear stress. The stress component parallel to a given surface, such as a fault plane, that results from forces applied parallel to the surface or from reinote forces transmitted through the surrounding rock. If you lean against the edge of the door where the latch is, you are applying shear stress to the door.

spectral acceleration or SA. PGA (peak acceleration) is what is experienced by a particle on the ground. SA is approximately what is experienced by a building, as modeled by a particle on a massless vertical rod having the same natural period of vibration as the building.

strong motion. Ground motion of sufficient amplitude and duration to be potentially damaging to a building or other structure.

surface faulting. Displacement that reaches the earth's surface during slip along a fault. Commonly occurs with shallow earthquakes, those with an epicenter less than 20 km. Surface faulting also may accompany aseismic creep or natural or man-induced subsidence.

surface wave. Seismic wave that travels along the earth's surface. Love and Rayleigh waves are the most common.