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**The Bam [Ms 6.6] Earthquake of December 26, 2003, SE Iran:
Engineering Seismological Aspects & Implications for the
U.A.E.**

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Abstract

The Bam [Ms 6.6] earthquake of December 26, 2003 of SE Iran is studied. The seismotectonics and faulting mechanism showed the reactivation of NS Bam fault with a right-lateral strike slip motion. Four fundamentally important source parameters, viz, M_0 , M_w , E_s and M_e were derived which corroborated and reflected the actual devastation that occurred in the city of Bam.

A hypothesis is introduced whereby the subducting Arabian Plate is advocated to undergo severe seismogenic crustal deformation that might end up causing it to rupture into two conspicuous segments.

Finally, the seismic hazard vulnerability of the United Arab Emirates is examined and an elaborate research program is proposed under the auspices of the University of Sharja's Research and Studies Center.

Archeoseismicity & Seismic Activity of Iran

Catastrophic earthquakes have frequently struck the Iranian plateau, characterized by active faulting, active folding, recent volcanic activity, and considerable elevation contrasts along the Alpine-Himalayan mountain belt, during recorded history (Berberian, 1997). These earthquakes have resulted in great loss of life and, by rendering large numbers of people homeless and disrupting the agricultural and industrial bases of their lives; Iran's gross domestic product (GDP) remains vulnerable.

Historical records of catastrophic earthquakes have survived for centuries. At least nine destructive earthquakes in Nishapur/Shadyak have reduced the size and changed the location of the city several times. Ray, another historical location, has been devastated at least six times in its recorded history. Almost all monuments in Tabriz were destroyed or severely damaged by at least eight large-magnitude earthquakes, especially by the one on 7 January 1780, which reduced all buildings to rubble. Unfortunately, except for the Blue Mosque (Masjed-e-Mozaffariya) built in 1465, the city now has very few historical monuments (Berberian, 1997). It is timely to mention at this juncture that the most useful and authoritative account of historical seismicity in Iran is given by Ambraseys & Melville (1982).

The Tabas-e-Golshan earthquake of 16 September 1978 [Ms 7.8] and the Rudbar-Tarom earthquake of June 1990 [Ms 7.4] were the most catastrophic earthquakes to have occurred in Iran in the 20th century. The Tabas-e-Golshan earthquake destroyed or severely damaged about ninety villages, slightly damaged another fifty villages in the region, and completely demolished the oasis town of Tabas-e-Golshan, where 85 percent of the inhabitants (11,000 out of 13,000) perished. Total fatalities were more than 20,000 with thousands injured. This earthquake, strongly felt over an area of 1,130,000 square km, destroyed over 15,000 housing units and thirty qanats (irrigation channels) in the epicentral region.

The Rudbar-Tarom earthquake, the largest in this century to affect an urban area in Iran, killed over 40,000 people, injured 60,000, and left more than 500,000 homeless. The earthquake destroyed three towns (Rudbar, Manjil, and Lowshan) and 700 villages and damaged another 300 villages in Gilan and Zanjan provinces of northwest Iran, southwest of the Caspian Sea. Nearly 100,000 buildings were destroyed or badly damaged. Water supplies in 283 villages were destroyed or reduced by 70 percent of total pumping capacity.

Insofar as the *modern* seismic activity of Iran is concerned, we need only to scrutinize the recent seismicity map (shown in Fig. 1) of the country during the decade 1990 – 2000 developed by researchers in the International Institute of Earthquake Engineering & Seismology in Iran (IIEES, 2003). This remarkably telling map clearly illustrates the

huge seismic activity on the *SUBDUCTING Arabian Plate* (i.e, the southwestern part of Iran) compared to the less active *OVERRIDING Eurasian Plate* towards the northeast thus shedding light on the seemingly *fast rate of subduction of about 3 cm/yr* in the region. However, there appears to be a *leaking corridor* of earthquake activity trending SW-NE just where the *plate BOUNDARY* makes a *sharp bend* from a N-S to a NW-SE direction. Fig. 2a & b [which show a decade, 1990-2000, worth of seismicity in Iran and the moment tensor fault mechanisms of 16 significant shocks over the 22 year period between 1981-2002] schematically illustrates the trace of such a corridor. This intensely active and concentrated region of strain energy release -which the Bam shock is integral to - might well be the site for the future *BREAK-UP* of the *subducting Arabian plate* into two segments, viz, a NS segment that is relatively *a seismic* compared to the *BREAK-AWAY* NW-SE segment. We therefore strongly suggest that this break-up and eventual separation of both segments appears to be not only *seismotectonically achievable* but *seismogenically imminent* – may be within the next few million years or so.

The BAM Earthquake Disaster

A strong and devastating earthquake occurred in the very early hours of Friday 26th December 2003 in the proximity of the town of Bam in southeastern Iran. With a surface wave magnitude of Ms 6.6 and a hypocentral depth of about 10 km, the United States Geological Survey (USGS) determined the epicentral location to be 29.0 N; 58.3 E. This location most probably indicates that the vast seismic energy released is attributed to the re-activation of the Bam fault where fresh surface faulting was observed between the towns of Bam and Baravat. Such an observation is corroborated by the more than 90 aftershocks, which occurred in the vicinity of the main shock up to January 7th, 2004 (see Fig. 3). Reaching a death toll of almost 40,000 inhabitants, 85% of the town buildings were damaged beyond repair, historical monuments like Arg-i-Bam was totally damaged and reduced to rubble (see Fig. 4). The shock was substantially felt in the provincial city of Kerman [*Ii = VIII*] 185 km to the northwest and achieved a maximum observed meioseismic intensity [*Io = IX*] at the town of Bam (see Fig. 5). The strong motion accelerometers registered vertical ground accelerations as much as 0.99 g (see Fig. 6).

Seismotectonics & Faulting Mechanism

From the seismotectonic point of view, the USGS as well as many other researchers, advocate that the focal mechanism of this earthquake – as is the case with many previous energy releases - occurred as the result of stresses generated by the extremely complex counter-clockwise crustal motion of the Arabian plate northward against the Eurasian

plate at a rate of approximately 3 cm/yr. Deformation of the earth's crust in response to the complicated plate motions in this region takes place in a broad zone that spans the entire width of Iran and extends into Turkmenistan. Mechanistically speaking and in a general sense, earthquakes occurring in this part of the globe are the result of both reverse as well as strike-slip faulting within the zone of deformation.

Preliminary analysis of the pattern of seismic-wave radiation from the Bam 2003 earthquake is consistent with the earthquake having been caused by right-lateral strike-slip motion on a north south oriented fault. The earthquake occurred in a region within which major north south, right lateral, strike-slip faults had been previously mapped, and the epicenter lies near the previously mapped, north south oriented, Bam fault.

It is worth pointing out that the Bam shock is only 100 km south of the destructive earthquakes of June 11, 1981 (magnitude 6.9, approximately 3,000 deaths) and July 28, 1981 (magnitude 7.3, approximately 1,500 deaths). These earthquakes were caused by a combination of reverse and strike-slip motion on the north south oriented Gowk fault. This could well be further evidence of our *Subducting Arabian Plate Break-Up Hypothesis*.

Earthquake Source Parameters

In order to fully describe the *rupture kinematics and dynamics* of the Bam earthquake, we need to look closely at four fundamentally important source parameters, viz, M_o , M_w , E_s and M_e . Respectively these source parameters are: *Seismic Moment, Moment Magnitude, Radiated Energy and Energy Magnitude*.

Employing the USGS moment tensor solutions for a double couple force equivalence used for shear faulting, the numerical value of M_o [Bam] is calculated to be: 6.6×10^{18} . To obtain M_w , we only require substituting M_o in Hanks & Kanamori's (1979) empirical equation. This leads to a value of M_w [Bam] = 6.5. Now, because M_w depends on M_o , which in turn is a volume description of the *SIZE* of the earthquake fault, M_w is taken to reflect a true measure of the ruptured area for the Bam shock as well as the final static displacement or *SLIP* vector on the actual fault surface.

Last but not least, we need to assess the radiated energy of the Bam earthquake, expressed as E_s . This was found to have a value of: 9.3×10^{14} N.m. Now, to get a physically accepted measure of the actual energy released in the Bam disaster, we use yet another magnitude scale developed by Choy & Boatwright (1995). Substituting for E_s , this empirical relationship gives: M_e [Bam] = 7.1.

Finally, it is worth noting that M_w & M_e do not conflict but rather complement each other. While M_w is *kinematic* in nature, i.e, it is derived from the *low-frequency*

asymptote of observed *ground displacement spectra*, M_e is determined from the recorded *high-frequency* content in the *ground velocity power spectra*. It therefore follows that M_e is a dynamic measure of the seismic potential for damage sustained by anthropogenic or man-made structures in Bam. To corroborate this argument, we can clearly state that the Excessively high value of M_e [Bam] is indeed a physically sound measure reflecting the actual devastation which actually occurred in the city of Bam where field observations determined that at least 85% of the local buildings and structures were rendered to heaps of brick and rubble.

Engineering Seismological Aspects

The principal aims of engineering seismological work is threefold:

1. Probabilistic Seismic Hazard Assessment & Determination.
2. Earthquake Risk Evaluation.
3. Strong Earthquake Ground Motion Characterization.

As an integral part of the Global Seismic Hazard Assessment Program – GSHAP (which ran over the period 1992-1999; see Giardini et al, 1999) – Tavakoli & Ghafory-Ashtiany (1999) have already achieved the first aim by producing the most elaborate SHA map for Iran. Fig. 7 is this 1:5,000,000 SHA map for Iran which depicts the probabilistic peak ground acceleration PGA in m/s^2 with 10% of exceedance [or 90% of non-exceedance] in 50 years of exposure time [or 475 years return period] employing a modified version of McGuire's (1978) FRISK software. Tavakoli & Ghafory-Ashtiany (1999) actually use 75 & 475 return periods in their map with SEISRISK III, a generative version of the landmark FRISK program (Bender & Perkins, 1987). A first glance at this phenomenal map, which we reproduce in Fig. 7, tells the tale since no other region in the world has such a unique and complicated picture relating to the dangers posed by one of the most elusive natural disasters in God Almighty's creation.

Using this SH zoning map and zooming-in on the location of the Bam earthquake we readily notice that the predicted PGA lies in the range of 4.0-4.8 m/s^2 . This value, which is nearly half the true-recorded value of 0.99 m/s^2 in Bam, grossly underestimates the real and most dangerous nature of the energy release in this and may be in many other areas of Iran. This is a good enough reason to recommend reviewing the whole map of Tavakoli & Ghafory-Ashtiany with the sole objective of re-calibrating the predicted PGA values with the corresponding *REAL* ones. In actual fact this stark contrast in predicted vs observed PGA's is not only not surprising but also quite expected. Studying the map of Fig. 8, which depicts the zonation of earthquake sources developed by Tavakoli & Ghafory-

Ashtiany (1999), we immediately come to notice that the Bam epicenter falls almost exactly on the triple junction joining zones 3,6 & 7. These three zones have been assigned maximum *OBSERVED* M_s values of 7.0, 7.4 & 7.3 respectively. Thus one possible source for the ill-correlation between predicted PGA values and observed M_s

values in the region under question are the inevitable approximations and sometimes the oversimplification inherent in the FRISK theoretical treatment and analytical approach. Another possible cause for the problem is the use of Tavakoli & Ghafory-Ashtiany (1999) attenuation equations which tend to oversimplify the true properties of the *Q upper crustal structure* beneath the Iranian Plateau which in turn helps little in deriving more realistic PGA values (see for example: Chandra et al, 1979; Campbell & Bozorgnia, 1994). Incidentally, continuing our scrutiny of Fig. 8, we note the excessively complicated hazard zonation produced by Tavakoli & Ghafory-Ashtiany (1999) just at the region where the *KINK* in the subduction boundary lies. Such a problematic zonation scenario is yet another striking proof that our *Break-Up Hypothesis* is a plausible one.

Turning our attention now to the task of estimating *the surface rupture length L (km), the rupture area A (sq-km) and the maximum surface displacement D (m)* produced by the Bam energy release we invoke the empirical equations relating M_w with the a/m parameters (see: Wells & Coppersmith, 1994) we arrive at the following results:

$$\begin{aligned} \mathbf{L [Bam]} &= \mathbf{18.2 \text{ km.}} \\ \mathbf{A [Bam]} &= \mathbf{269.1 \text{ sq-km.}} \\ \mathbf{D [Bam]} &= \mathbf{0.46 \text{ m.}} \end{aligned}$$

Finally, to get an idea about the age T (*million years*) of the subduction process of the Arabian Plate under the Eurasian Plate, we utilize the relationship developed by Ruff & Kanamori (1980) which brings together M_w with T and V ; V (*cm/yr*) being the rate of convergence of the two crustal plates. This gives an age of 190.5 million years.

Implications for the U.A E

The U.A.E is geographically, geologically and geophysically situated in a very *UNIQUE* location. Facing the subduction boundary just across the waters of Arabian Gulf, the tip of the country (i.e, the cities of Ajman and Ras Al Khaimah) lies opposite the Hormuz Straits, north of which is situated one of the most *NOTOREOUS* seismically active zones in the world. This situation necessarily implies that the U.A.E is not only exposed but is ultimately vulnerable to excessively large strong earthquake ground motions originating not too far a distance on the southern shores of Iran.

In order to formulate a preliminary idea about the expected PGA distribution within the Emirate, we simply enlarge the *extrapolated seismic hazard* zonations of Tavakoli &

Ghafory-Ashtiany (1999). This is schematically shown in Fig. 9. This map depicts the obvious fact that the northern parts of the country have higher seismic hazard than the southern parts, viz, the cities of Abu Dhabi, Dubai & Sharjah for PGA's with 10% probability of exceedance in a 50 year exposure time. However, and as elaborated earlier from the standpoint of inconsistencies in the predicted vs the actual PGA values, we can only conclude that this rather *PRIMITIVE* first estimate warrants not only *re-evaluation* but *certainly re-vamping!* This will be the subject matter of an elaborative research

program to be undertaken by the authors (see for example: Fahmi, 1996; Fahmi et al, 1996; Malkawi & Fahmi, 1996; Fahmi & Malkawi, 1998) in collaboration with the Research & Studies Center at the University of Sharjah. It is worth noting here that the work recently done by Abdallah (2003) is a good step in the right direction.

Conclusions

Based on the results presented in this research, the following conclusions may be drawn:

1. The facts and figures produced by the Bam earthquake disaster **MUST & SHOULD** be carefully and thoroughly evaluated from the geophysical, seismological and geotechnical earthquake engineering points of view with the intention of exploiting the complete Bam disaster portfolio to re-assess and re-evaluate seismicity and seismic hazards in Iran.
2. We introduce an **HYPOTHESIS** whereby the *Subducting Arabian Plate* is advocated to undergo severe seismogenic crustal – **currently PLASTIC** – deformation that might end up causing it to **RUPTURE** into **TWO conspicuous segments** possibly within the next few million years.
3. The seismic hazard **VULNERABILITY of the U.A.E** urgently warrants immediate elaborate and detailed research to produce more **REALISTIC** estimates of possible future seismically hazardous ground motions anticipated to arrive from the northern or even the northwestern shores.

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FIGURES

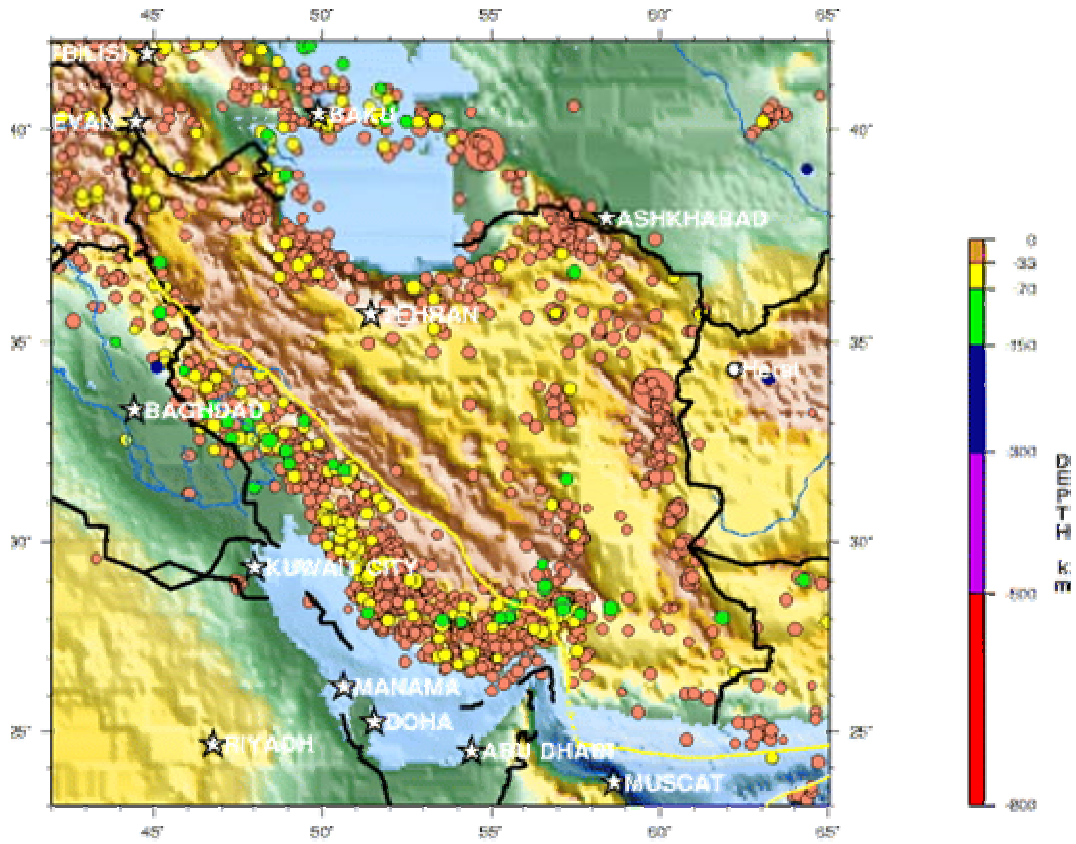


FIG. 1. Seismicity of Iran 1990-2000 Illustrating the *Huge* Seismic Activity on the Subducting Arabian Plate (IEEE,2003).

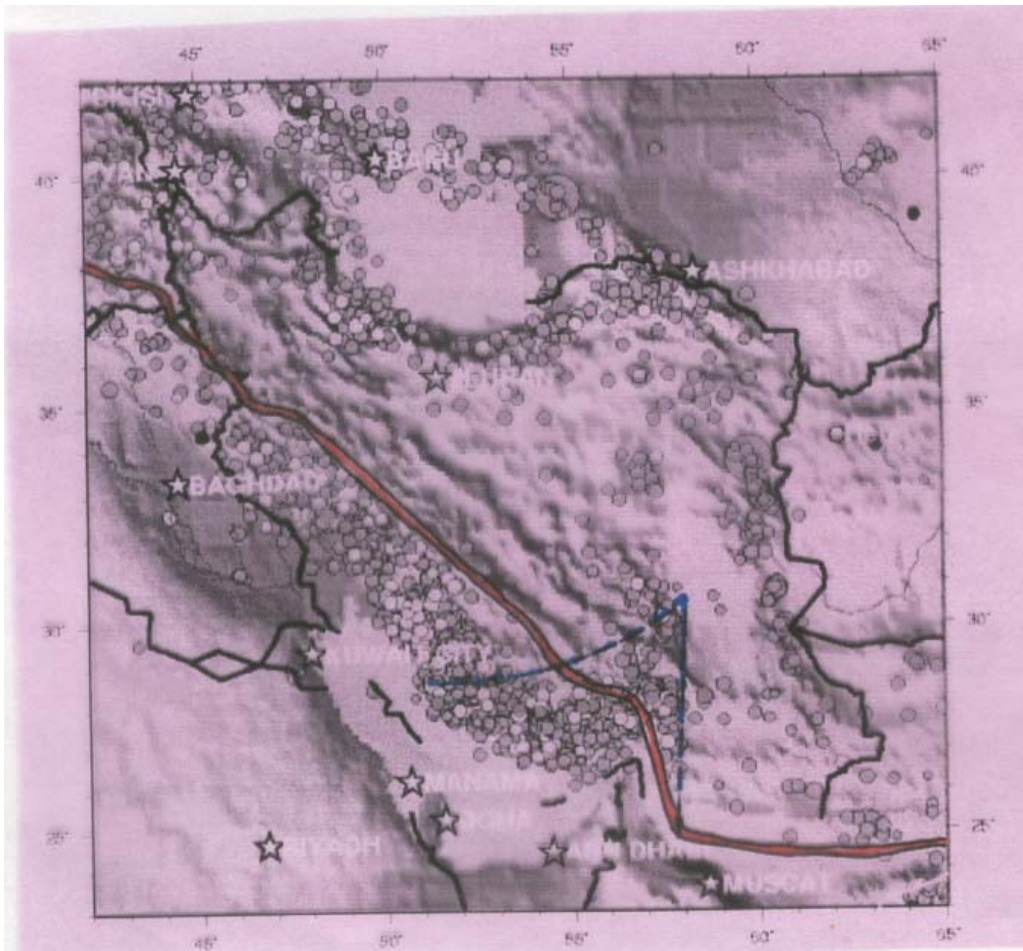


FIG. 2a. A decade (1990-2000) worth of seismicity in Iran with the boundary of the subduction zone sketched-in.

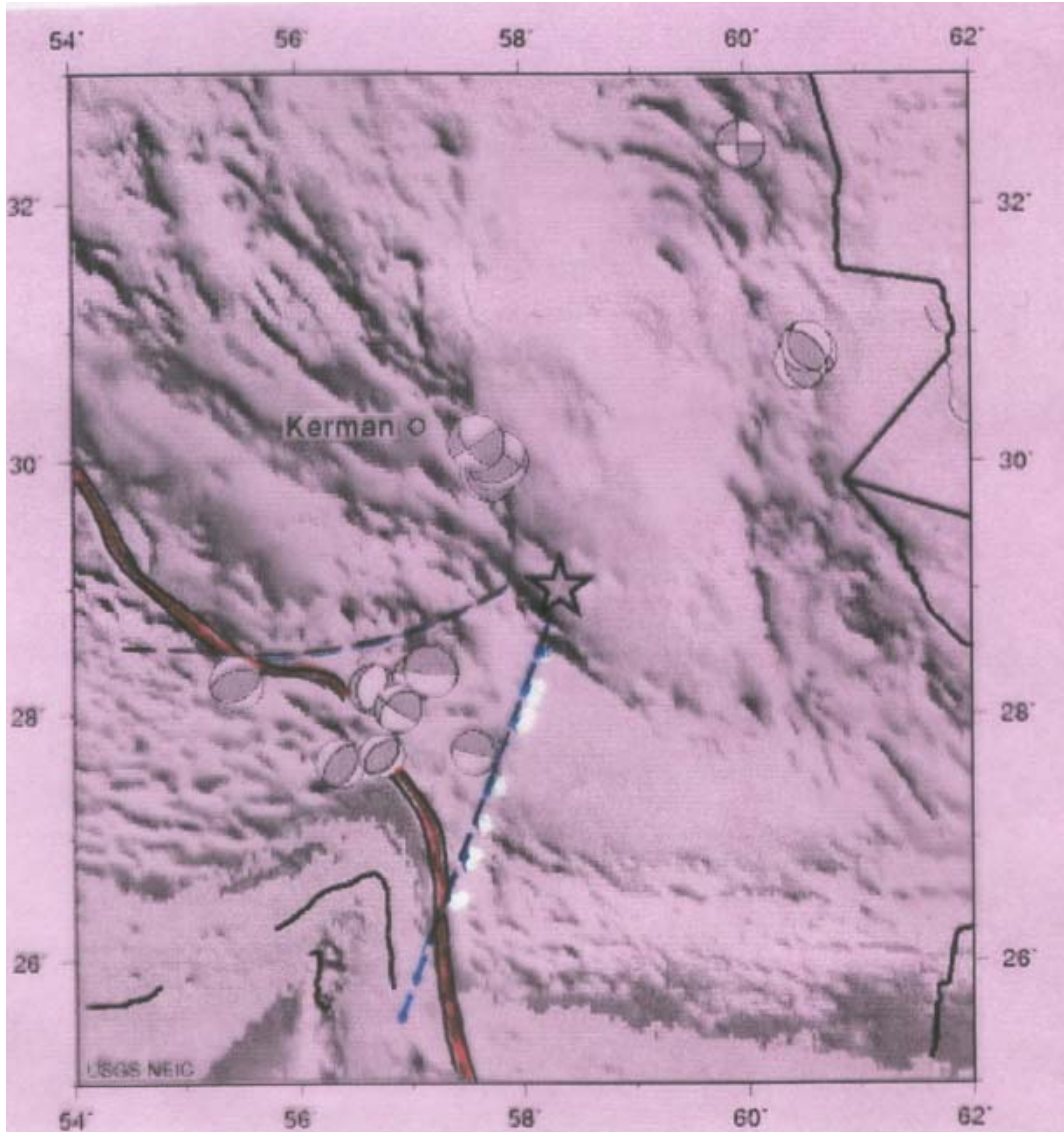


FIG. 2b. Location of the Bam [December 2003] Earthquake with the moment tensor fault mechanisms of 16 significant shocks during 1981-2002, schematically illustrating the boundaries of the hypothesized *Leaking Corridor*.

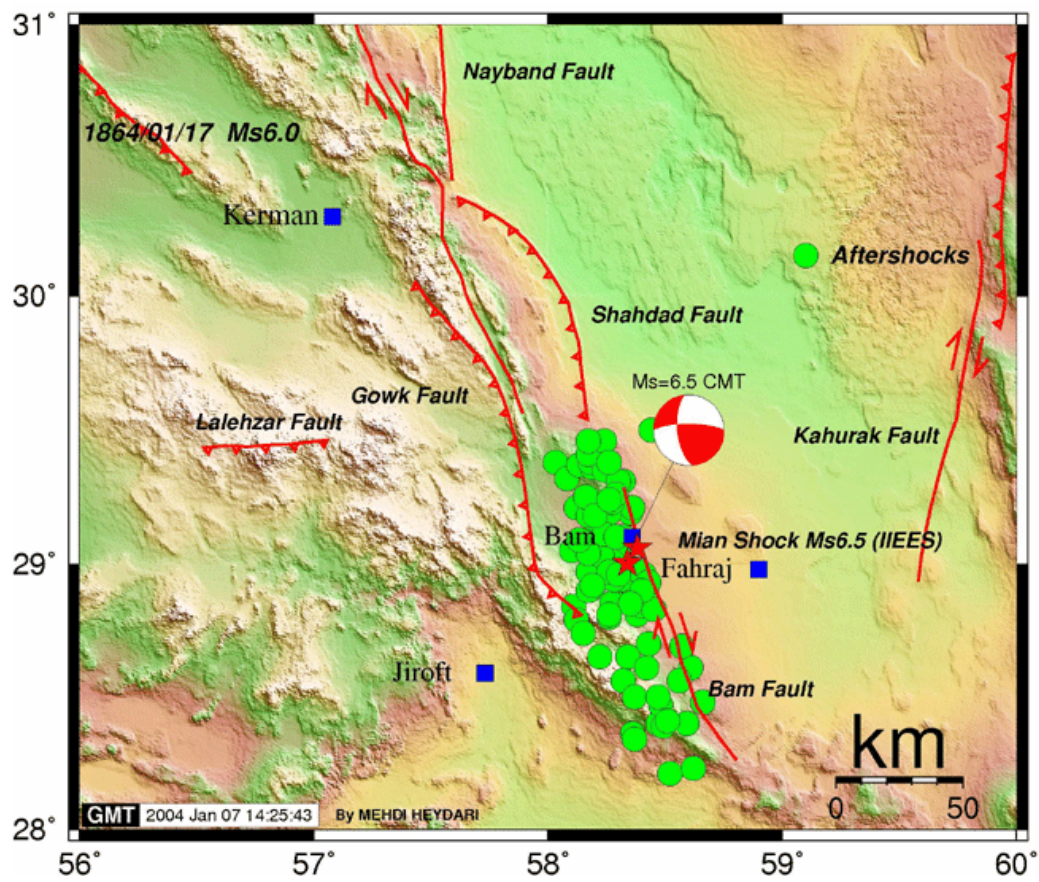


FIG. 3. Re-activation of the Bam fault as evidence by the Bam main shock and more than 90 aftershocks up to January 7th, 2004. (IIEES, 2003).



FIG. 4. Arg-i-Bam, over 2000 years old, Iran's Ancient City, destroyed during the earthquake. (IEES, 2003)

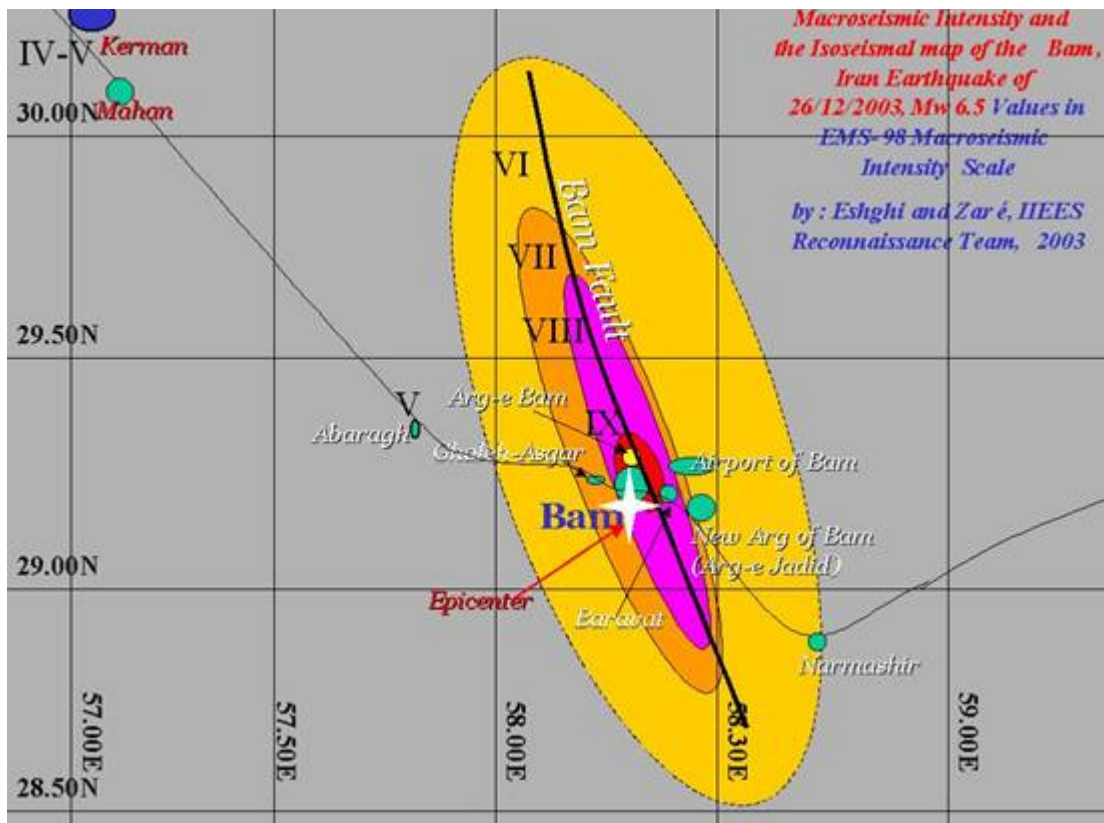


FIG. 5. The Macroseismic intensity and the isoseismal map of the 26/12/2003 Bam earthquake after Eshghi and Zare (2003).

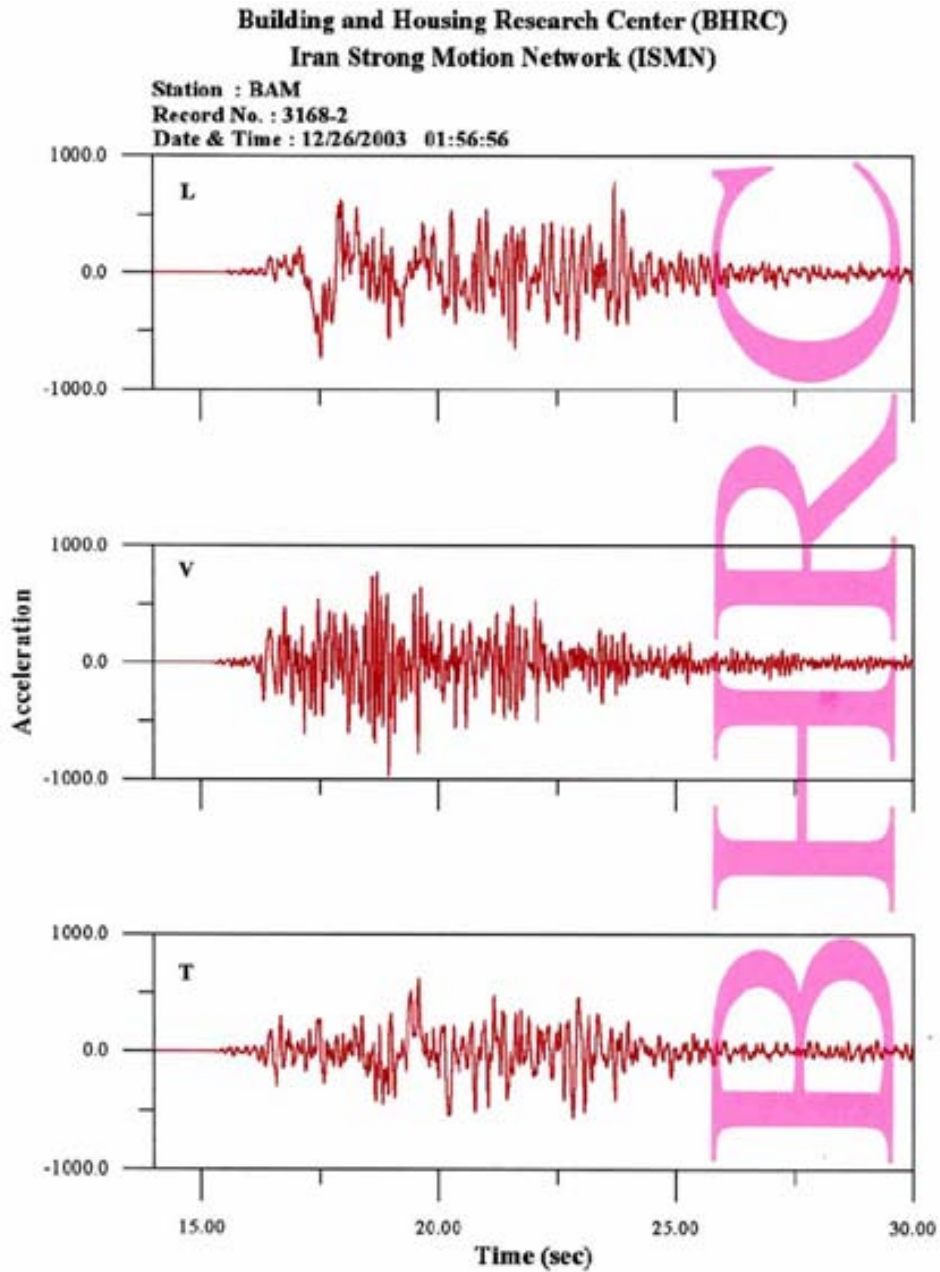


FIG. 6. Recorded acceleration time histories at Bam December 2003 earthquake (IIEES, 2003)

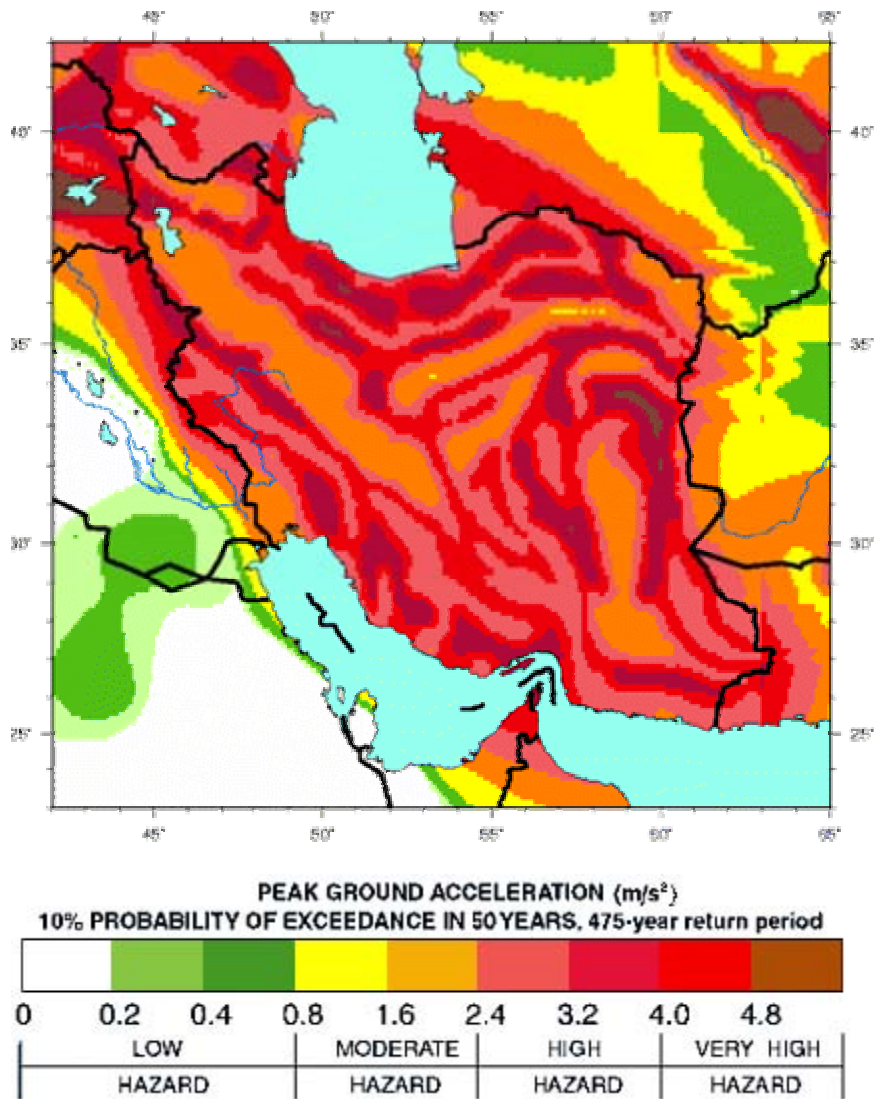


FIG. 7. Seismic Hazard Map for Iran (Tavakoli & Ghafory-Ashtiany, 1999)
 [PGA (m/s²) values with 10% Probability of Exceedance in 50
 years of Exposure].

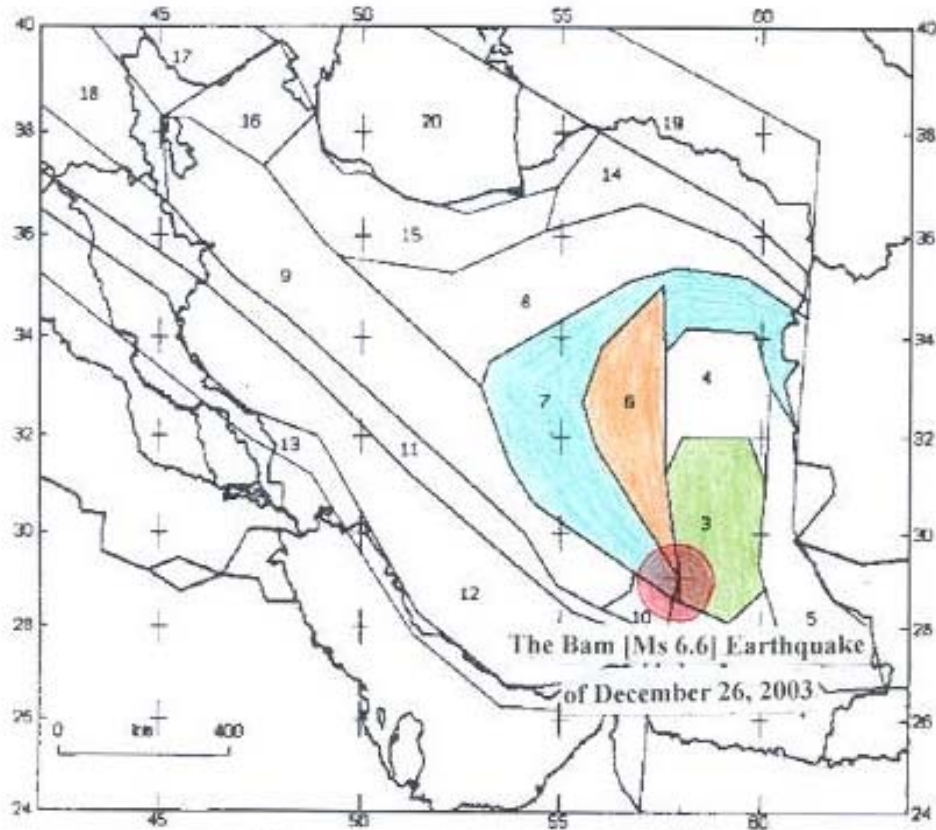


FIG. 8. The Triple Junction of the three seismic hazard sources, viz 3,6 & 7
 Determined by Tavakoli & Ghafory-Ashtiany (1999)
 Showing the Bam Epicentral Location

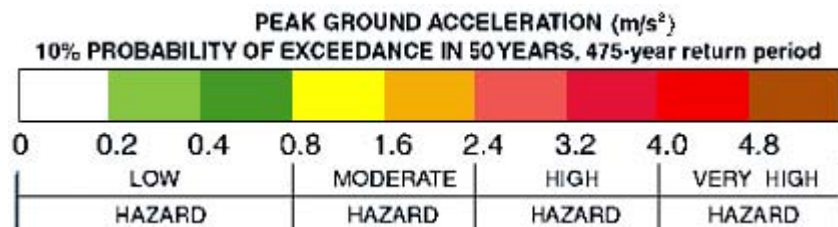
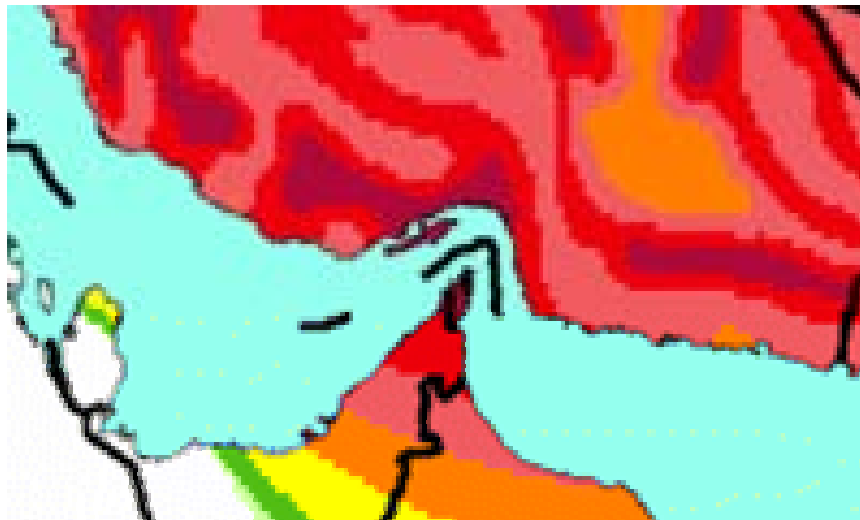


FIG. 9. Schematic Extrapolation of the Seismic Hazard Zonation For the United Arab Emirates Developed by Tavakoli & Ghafory-Ashtiany (1999) [PGA (m/s^2) values with 10% Probability of Exceedance in 50 years of Exposure].