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# Evaluation of the seismic hazard of Lebanon

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## Abstract

This paper presents the results of a study undertaken to determine the seismic hazard of Lebanon. The seismic hazard evaluation was conducted using probabilistic methods of hazard analysis. Potential sources of seismic activities that affect Lebanon were identified and the earthquake recurrence relationships of these sources were developed from instrumental seismology data, historical records, and earlier studies undertaken to evaluate the seismic hazard of neighboring countries. The sensitivity of the results to different assumptions regarding the seismic sources in the Lebanese segment and choice of the attenuation relationship was evaluated. Maps of peak ground acceleration contours, based on 10 percent of probability of exceedance in 50 years and 100 years time spans, were developed.

## Introduction

A quick review of the seismic activity in Lebanon and the Eastern Mediterranean clearly demonstrates that this part of the world has been shaken since 2000 B.C. by strong earthquakes that destroyed thousands of structures and caused severe casualties and loss of human life in present day Lebanon, Syria, Jordan, Israel and Palestine. Three earthquakes stand out in the history of seismic activities in Lebanon: the earthquakes of 551 A.D., 1202 A.D and 1759 A.D (two events). The magnitudes of these earthquakes were estimated, based on historical accounts, to be in excess of 7.0, and caused destruction in most coastal cities including Beirut, Tripoli, Jubail, Saida, and Tyre as well as the ancient city of Baalbeck.

Occupying 225 km of the 600 km long segment making up the Eastern Mediterranean coastal region, Lebanon lies right across an estimated 1000 km long fault which extends from the seafloor spreading in Red Sea to the Taurus mountains in southern Turkey (Figure 1). This fracture system, known as the levantine or Dead Sea system (Beydoun, 1977), is an extremely important tectonic feature, which accounts for the bulk of seismic activity in the Eastern Mediterranean.

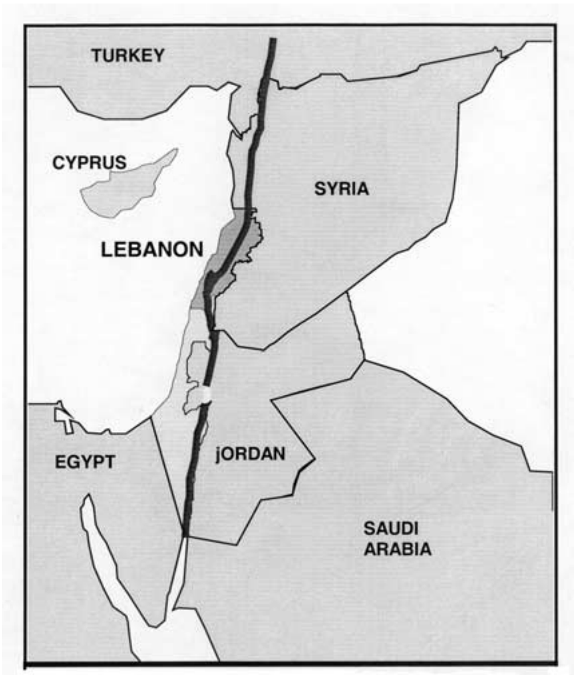

*Figure 1.* The levantine fracture system.

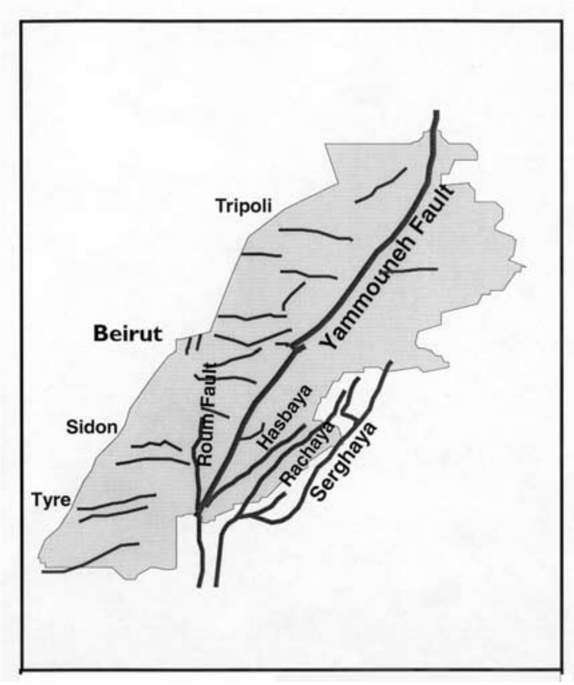


*Figure 2.* Fault setting in Lebanon.

In its Southern segment, which extends from the Gulf of Aqaba to the Sea of Galilee and the Hula depression in south Lebanon, the Dead Sea fault system strikes in a more or less N-S direction. However, when entering Lebanon through the Galilee heights, it changes into a more complex system of braided strike-slip faults (Wally 1988), known as *Roum, Yammouneh, Hasbaya, Rachaya, and Serghaya* (Figure 2). The most significant among these faults is the *Yammouneh* which forms the western boundary of the Bekaa valley, and which represents the main northward continuation of the Dead Sea fault system to the *Ghab* fault in Syria, and then on to the *Taurus-Zagros* thrust in southern Turkey.

Historically, the Levant fracture system has given rise, at its Southern and Northern segments and in different time intervals, to major destructive earthquakes of varying magnitudes (Plassard and Kogoj, 1981; Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989). According to Ambraseys and Barazangi (1989), during the last millennium alone, more than 8 strong earthquakes with magnitude greater than 6.5 have struck along the northern continuation of the Dead Sea fault in Lebanon and Syria. Furthermore, earthquakes on the seabed between Cyprus and Lebanon, some of which are close to the coastal line, are very frequent. These earthquakes may affect a large number of heavily populated and developed cities and towns along the coastal belt of Lebanon.

The last sizable inland earthquake that struck Lebanon in the past century is the double shock of March 16, 1956. The epicenter was estimated close to the northern tip of the *Roum* fault and the magnitude was measured at 5.8 by the Seismological Observatory in Lebanon. This earthquake left 136 dead, 6000 homes destroyed and about 17000 heavily damaged. More recently, an earthquake of magnitude 5.3 struck Lebanon on March 21, 1997. The epicenter was estimated by the Bihanness Seismological Observatory to be almost at the same location (Roum fault) as the double shock of March 16, 1956. The earthquake reached Beirut with an intensity of about VI on the Modified Mercalli (MM) intensity scale and resulted in high levels of shaking for a short duration of about 6 seconds. This earthquake caused slight damage (wall cracking) of a few stone buildings and resulted in a few cases of nonstructural damage (broken windows and cladding, and hair cracking of infill walls) at the upper stories of reinforced concrete buildings. No loss of human lives was reported.

Given the location of Lebanon on the seismic map, it can be stated that Lebanon is indeed a seismic prone country. Because of the importance of earthquake activity in the Eastern Mediterranean and the potential danger associated, several studies and research efforts have attempted to evaluate the seismic hazard of neighboring countries (Ben-Menahem, 1979, 1981; Ben-Menahem and Abodi, 1981; El-Isa and Hasweh, 1986; Qa'dan, 1987; Yucemen, 1992; Shapira and Arieh, 1993; Al-Haddad et al., 1994; Malkawi et al., 1995).

This paper presents the results of a study that was undertaken to evaluate the seismic hazard of Labanon. A catalogue of seismic events that includes both instrumental and historical data was developed, the seismic sources that affect the hazard in Lebanon were identified, and the recurrence relationships of these sources were generated. The hazard results are presented in map of peak ground acceleration contours based on 10 percent probability of exceedance in 50 years and 100 years exposure time.

A brief description of the hazard analysis method used in this study is provided in the following section.

## Description of hazard analysis method

The seismic hazard evaluation was conducted using the probabilistic method of hazard analysis introduced by Cornell (1968) and McGuire (1978). This method is based on Poisson's distribution of the earthquake arrival process. It requires, basically, identification of the seismic sources and establishment of their earthquake recurrence relationships developed in accordance with the Guttenberg-Richter law, and the use of a ground motion attenuation relationship relevant to the region under investigation.

Guttenburg-Richter recurrence law (Gutternberg and Richter, 1956; Richter, 1958) is expressed as follows:

$$Log(N \geq m) = a - bm \tag{1}$$

Where m is the earthquake magnitude and N is the number of earthquakes with magnitude $\geq m$ per annum. Equation (1) can be re-written as:

$$N(m) = e^{\alpha - \beta m} \tag{2}$$

Where $\alpha$ = a.*Ln10*, and $\beta$ = b.*Ln10*. For engineering applications, the effect of earthquakes of magnitude less than a minimum value ($m_o$) on the experienced structural and nonstructural damage through ground shaking is likely to be insignificant. Therefore, by eliminating the range of magnitudes of $m_o$ and smaller, Eq. (2) can be rewritten as:

$$N(m) = \nu e^{-\beta(m - m_o)} \tag{3}$$

Where:

$$\nu = e^{\alpha - \beta m_o} \tag{3a}$$

The probability of occurrence of an earthquake with magnitude less than 'm' but greater than $m_o$ can be expressed using the cumulative distribution function as follows:

$$F_M(m) = P(M < m | M > m_o) = \frac{N(m_o) - N(m)}{N(m_o)} = 1 - e^{-\beta(m - m_o)} \tag{4}$$

Considering the ultimate earthquake magnitude $m_u$ that the seismic source is capable of producing as the other limit of the magnitude scale, the probability that $M < m_u | M > m_o$ is different from 1 in accordance with Eq. (4). Therefore, $F_M(m)$ is redefined (McGuire and Arabasz, 1990) to take into account the upper and lower bound magnitudes as follows:

$$F_M(m) = P(M < m | m_o < m < m_u) = \frac{1 - e^{-\beta(m - m_o)}}{1 - e^{-\beta(m_u - m_o)}} \tag{5}$$

The probability density function is expressed as:

$$f_M(m) = \frac{dF_M(m)}{dm} = \frac{\beta e^{-\beta(m - m_o)}}{1 - e^{-\beta(m_u - m_o)}} \tag{6}$$

Considering a Poisson model of earthquake arrival process, the probability that a ground motion parameter A exceeds a value 'a' within a certain time period 't' at a given site is expressed as follows:

$$P(A > a) = 1 - e^{\lambda_a t} \tag{7}$$

Where:

$$\lambda_a = \sum_{i=1}^{N_s} \lambda_{ai} \tag{8}$$

In which $\lambda_a$ is the mean annual number of earthquake events resulting in $A > a$ at a given site, $N_s$ is the number of earthquake sources, and $\lambda_{ai}$ is the mean annual number of earthquake events resulting in $A > a$ at source i. $\lambda_{ai}$ is expressed using the total probability theorem as follows:

$$\lambda_{ai} = \int_M \int_R \nu_i f_{M_i}(m_j).P(A > a | m_j, r_k). f_{Ri}(r_k) dm\, dr \tag{9}$$

In which:

$$\nu_i = \text{total annual exceedance rate for source } i = e^{\alpha_i - \beta_i m_o} \tag{9a}$$

$$f_{M_i}(m_j) = \frac{\beta e^{-\beta(m_j - m_o)}}{1 - e^{-\beta(m_u - m_o)}} \tag{9b}$$

$f_{R_i}(r_k)$ = Probability density function for distance, and $P(A > a | m_j, r_k)$ is the probability that the ground motion exceeds the specified level 'a' given an earthquake of magnitude $m_j$ at distance $r_k$.

By dividing the range of increments between $m_o$ and $m_u$ into $N_M$ magnitudes $\Delta$m, and the area or line source into $N_R$ small increments of distance $\Delta$r to the site, it is possible to evaluate the integral in Eq. (9) numerically using the following equation:

$$\lambda_{ai} = \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} \nu_i f_{M_i}(m_j).P(A > a | m_j, r_k). f_{R_i}(r_k) \Delta m \Delta r \tag{10}$$

or

$$\lambda_{ai} = \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} \nu_i P(M = m_j).P(A > a|m_j, r_k).$$

$$P(R = r_k) \tag{11}$$

In order to reflect the uncertainty in the amplitude of ground motion, the magnitude of $A$ at a specific distance from the seismic source as obtained from the ground motion attenuation equation is assumed to be log-normally distributed, thus:

$$P(A > a|m_j, r_k) =$$

$$1 - \Phi \left\{ \frac{Ln(a) - [Ln\hat{A}|m_j, r_k]}{[\sigma_A|m_j, r_k]} \right\} \tag{12}$$

$\Phi\{\}$ is the cumulative distribution function of a standard normal variable; $[\hat{A}|m_j, r_k]$ is the median value of A caused by earthquake of magnitude $m_j$ at distance $r_k$, obtained from the attenuation relationship; and $[\sigma_A|m_j, r_k]$ is the logarithmic standard deviation of $A$.

## Seismic sources and earthquake recurrence relationships

The seismic sources and their earthquake recurrence relationships were determined by compiling instrumental as well as historical earthquake data pertaining to the seismic activity inside Lebanon and vicinity (Plassard and Kogoj, 1981; Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989), and by relying in part on earlier studies undertaken to evaluate the seismic hazard of neighboring countries. A catalogue of historical and instrumental seismic records in this part of the world, going back to 1365 B.C., is presented by Harajli et al. (1994).

Since the seismic hazard evaluation of Lebanon is mainly influenced by the seismic activity within the country or at a close proximity to it, a particular effort was made to define the seismic sources and establish the earthquake recurrence relationship in the Lebanese segment. In addition to a region defined as the Lebanon region, two neighboring and potentially contributing areas were identified. They are noted as the Mediterranean region, and the Southern segment of the Dead Sea fault, respectively. In what follows the sources are further described and their seismic characteristics presented.

### *Neighboring regions*

Two additional seismic sources were considered as they may influence the seismic hazard analysis of Lebanon, in addition to the northern extension of the Lebanese system inside Syria for which the earthquake recurrence relationship as developed for the Lebanon segment are assumed to apply:

(a) *Southern segment of the Dead Sea fault*: Modeled as a line source, it extends in a S-N direction from the southern part of the Dead Sea (Latitude 31.0°N, Longitude 35.4°E) to the Galilee heights in south Lebanon (Latitude 33.3°N, Longitude 35.6°E), with a total length of about 256 km. This segment is represented in Figures 8 and 9.

(b) *Mediterranean region*: Modeled as an area source, it includes earthquake activity south of Cyprus. This area source is bounded approximately between Longitudes 32°E and 34.9°E, and Latitudes 33.5°N and 35.3°N, with an approximate area of 50,000 sq.km. This area is also represented in Figures 8 and 9.

Several studies have concentrated on evaluating the seismic activity of these sources and many equations were proposed to describe their earthquake recurrence relationships (Ben-Menahem, 1979, 1981; Ben-Menahem and Abodi, 1981; El-Isa and Hasweh, 1986; Qa'dan, 1987; Yucemen, 1992). In this study, the annual earthquake recurrence relationships proposed by Yucemen (1992) were adopted:

*Southern segment of the Dead Sea fault*

$$Log(N \geq M) = 2.64 - 0.75M \tag{13}$$

*Mediterranean region*

$$Log(N \geq M) = 1.40 - 0.45M \tag{14}$$

Based on historical records and rupture length-magnitude relationships, the maximum earthquake magnitude for the Dead Sea fault and the Mediterranean Region were estimated (Yucemen, 1992) to be 7.5 and 7.0, respectively.

### *The Lebanon region*

A map showing the epicenter of instrumental earthquake events with local magnitudes greater or equal to 3.0, which occurred inside Lebanon or close to its territories for the period 1903–1999 is shown in Figure 3. The instrumental records used comprise 100 events of

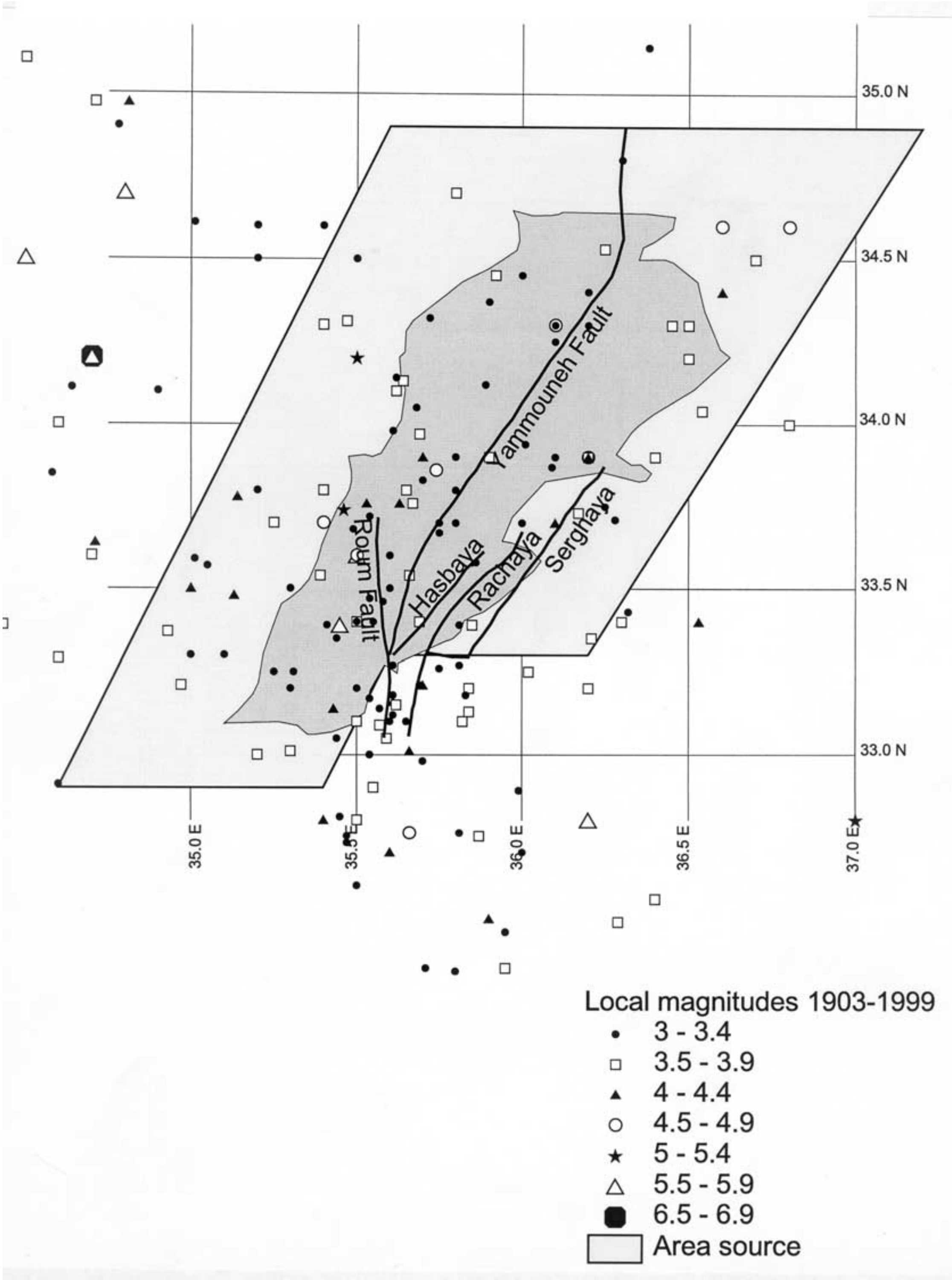


*Figure 3.* Instrumental earthquake events between 1903–1999 and proposed seismic area source for hazard analysis of Lebanon.

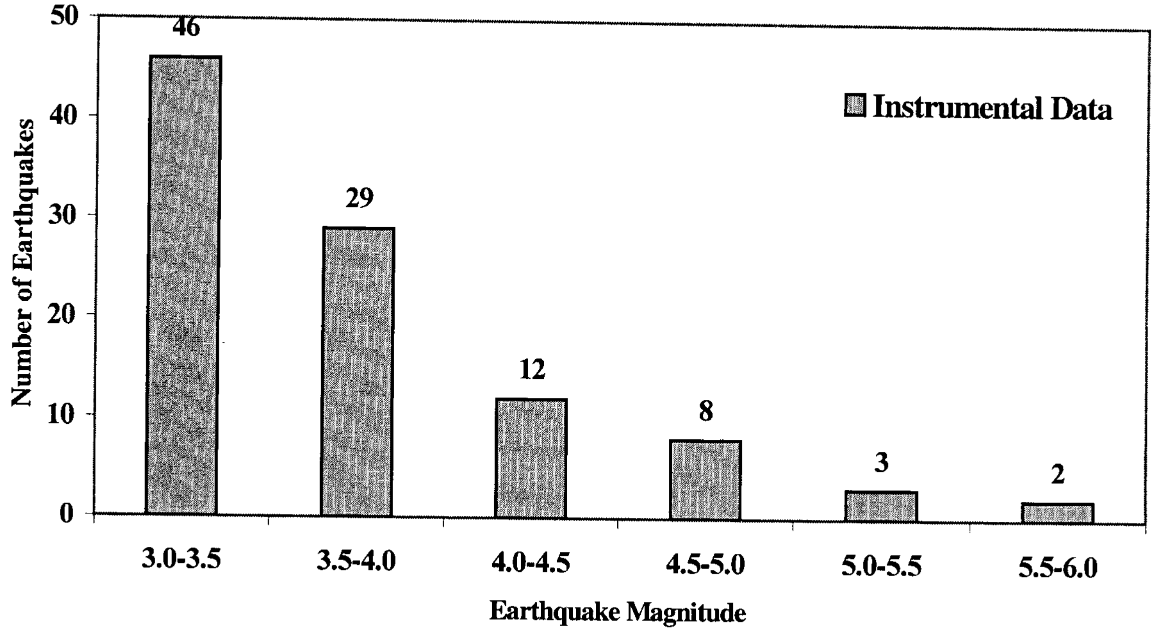


*Figure 4.* Breakdown of instrumental earthquake records (1903–1999) by magnitude.

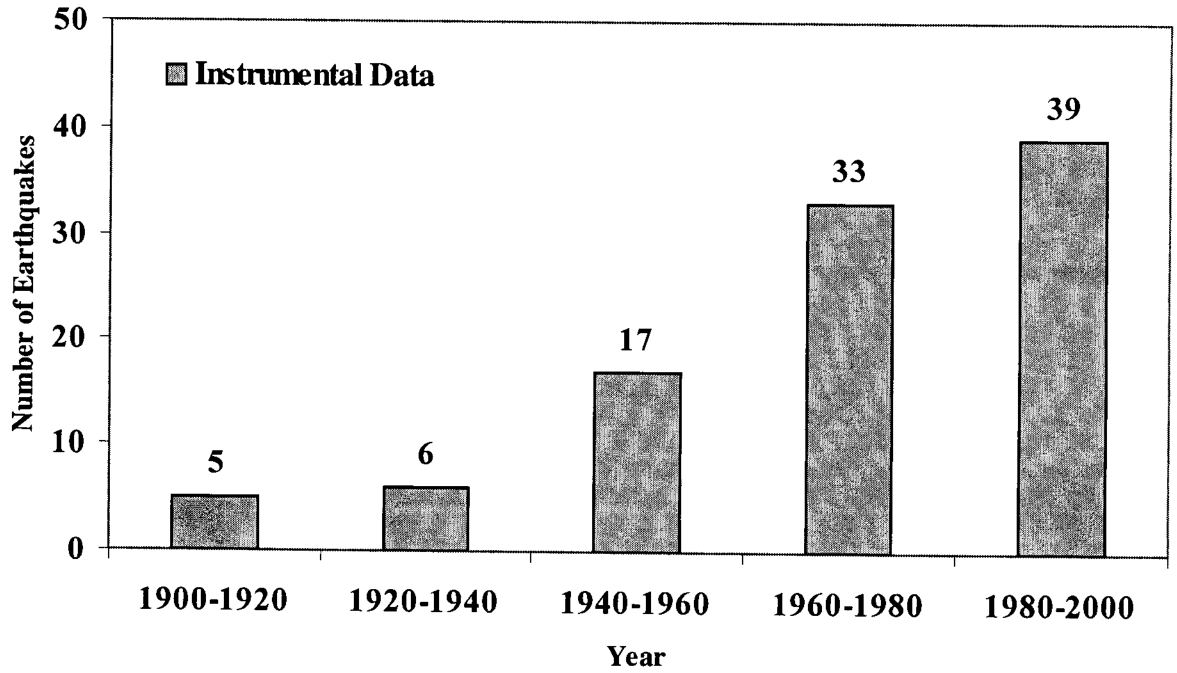


*Figure 5.* Breakdown of instrumental earthquake records (1903–1999) by 20 year segments.

| Date | °N | °S | $M_s$ | Locality |
|---|---|---|---|---|
| Aug15, 1157 | 35.1 | 36.3 | > 7.0 | Hama |
| June 29, 1170 | 35.9 | 36.4 | > 7.0 | Idlib |
| May 20, 1202 | 34.1 | 36.1 | 7.5 | Baalbek |
| Feb. 22, 1404 | 35.9 | 36.3 | Large | Hatab |
| April 29, 1407 | 35.7 | 36.3 | ~ 7.0 | Orontes |
| Oct. 30, 1759 | 33.1 | 35.6 | 6.6 | S. Bekaa |
| Nov. 25, 1759 | 33.7 | 35.9 | 7.4 | Bekaa |
| April 26, 1796 | 35.7 | 36.0 | 6.6 | Ladhikiya |
| Aug. 13, 1822 | 36.7 | 36.9 | 7.4 | Aafrine |
| April 3, 1872 | 36.4 | 36.5 | 7.2 | Amik Golu |

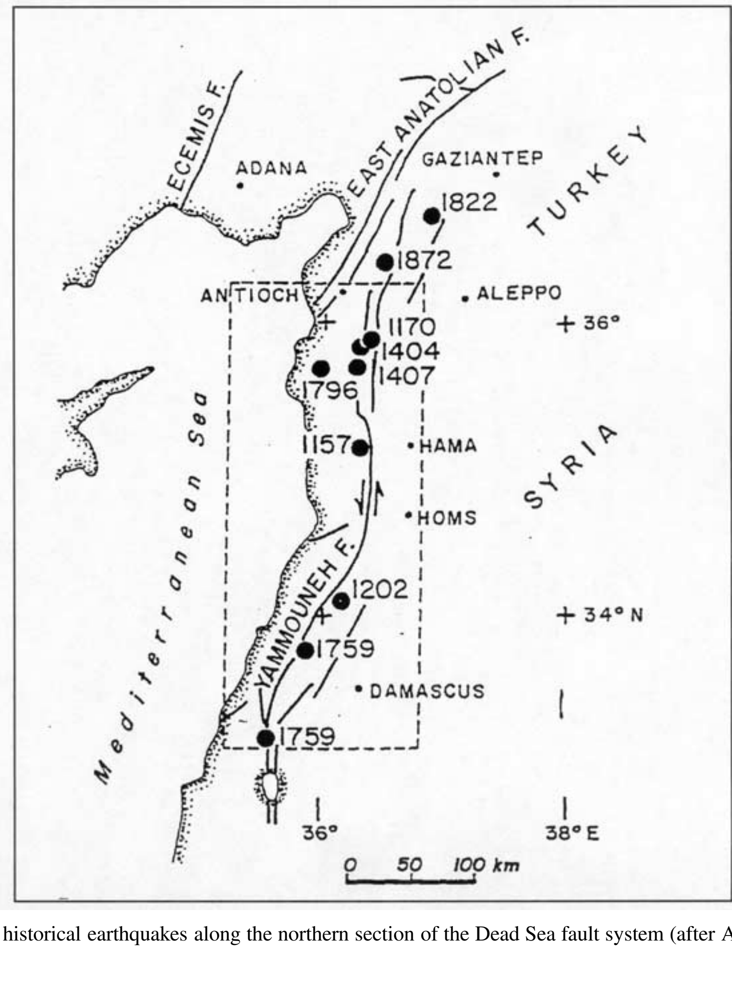


*Figure 6.* Distribution of large historical earthquakes along the northern section of the Dead Sea fault system (after Ambraseys and Barazangi, 1989).

magnitude ranging from 3.0 to 6.0. A complete breakdown and representation of the instrumental data by magnitude and time span is included in Figures 4 and 5. Major historical earthquake events that took place along the northern continuation of the Dead Sea fault system since 1100 AD are summarized in Figure 6.

The following relevant observations and assumptions were considered for modeling the seismic sources and deriving their earthquake recurrence relationships:

(i) The seismic events triggered by the fault system in the Lebanese segment under evaluation are enclosed within the area zone defined in Figure 3 (area = 25,000 sq.km). The earthquakes bordering the prescribed zone to the south are assumed to belong to another seismic source, namely, the southern segment of the Dead Sea fault system discussed earlier.

(ii) Since geological studies to predict the maximum earthquake magnitude are not available for the fault system in Lebanon, it is necessary to rely on historical records and to assume, with reasonable accuracy, that the maximum earthquake magnitude in the Lebanese segment is equal to 7.5. This magnitude is also consistent with the one proposed by Yucemen (1992) for the Dead Sea fault system used in studying the seismic hazard of Jordan and vicinity. However, the analyses presented in this paper include both the base case with a value of $m_u = 7.5$ and a similar analysis using $m_u = 7.0$ in order to evaluate the sensitivity of the results to the assumption made regarding the maximum earthquake magnitude.

(iii) According to Ambraseys and Barazangi (1989), the historical earthquakes shown in Figure 6 had struck along a 350 km long stretch of the northern continuation of the Dead Sea fault system in three short periods of paroxysmal activity in 1157–1202, 1404–1407, 1759–1796, about 200 to 350 years apart. Assuming equal probability of earthquake occurrence anywhere along this stretch, the conservative return period of 200 years, taken to correspond to the maximum earthquake of magnitude 7.5, is equivalent to a return period of about 450 (say 500) years along the approximately 150 km long northerly stretch inside Lebanon. This proposed return period for the maximum earthquake is compatible with the return period of about 550 years between the May 20, 1202 earthquake (magnitude evaluated at 7.5) and the November 25, 1759 (magnitude evaluated at 7.4), which struck in the Bekaa plateau inside Lebanon (Figure 6).

Based on the observations and assumptions presented above, the following two seismic source models for the Lebanese segment were studied and the sensitivity of the results to each was evaluated:

*Model I:* This model is presented in schematic form in Figure 8. Lebanon and its surrounding region, with noticeable concentration of seismic activity (excluding the Dead Sea fault to the south which is represented as a separate source in the analysis) as shown in Figure 3, is modeled as one seismic area source (area = 25,000 sq.km) in which earthquakes of magnitude up to and including the maximum earthquake (M = 7.5) have equal probability of occurrence anywhere within this source. The selection of Lebanon as one seismic area source is justified on the basis that Lebanon is a relatively small country with a very complex fault structure running virtually in all directions, which makes the subdivision of its region into more than one seismic source, not only a difficult task, but also unwarranted.

The use of best-fit analysis of the instrumental earthquake data enclosed within the area shown in Figure 3 (area = 25, 000 sq.km), in conjunction with the Guttenberg-Richter recurrence law, leads to the following predicted annual earthquake recurrence relationship for a maximum earthquake $m_u = 7.5$:

$$Log(N \geq M) = 1.89 - 0.62M \qquad (15)$$

Where N is the cumulative number of earthquakes per annum of magnitude greater than or equal to M.

Comparison of Eq. (15) with instrumental records, and using a maximum earthquake magnitude of 7.5, is shown in Figure 7. For analyses in which the source is assumed to be capable of a maximum earthquake of 7.0, Eq. 15 becomes log $(N \geq M)$ = 2.17–0.69.

Note that the analyses based on model I, involve the contributions of the Lebanon region as described above, in addition to the contribution from the southern section of the Dead Sea fault system and the Mediterranean region both defined earlier.

*Model II:* This model is presented in schematic form in Figure 9. Large earthquakes (with magnitudes greater than 6) for the last 900 years or so had their epicenters along the *Yammouneh* fault and its northern continuation to the *Ghab* fault in Syria (Figure 6). As such, it is reasonable to assume that while earthquakes of magnitude $m \leq 6.0$ have equal probability of striking anywhere within the area source defined in

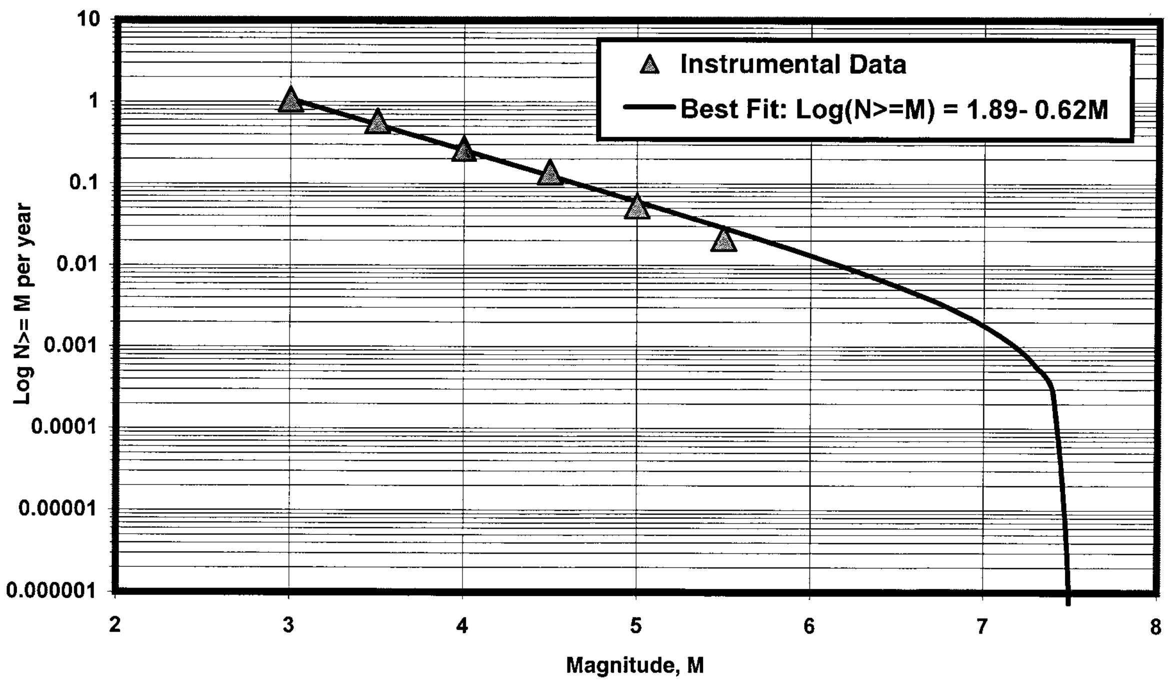


*Figure 7.* Predicted magnitude-frequency relationship for $m_u = 7.5$.

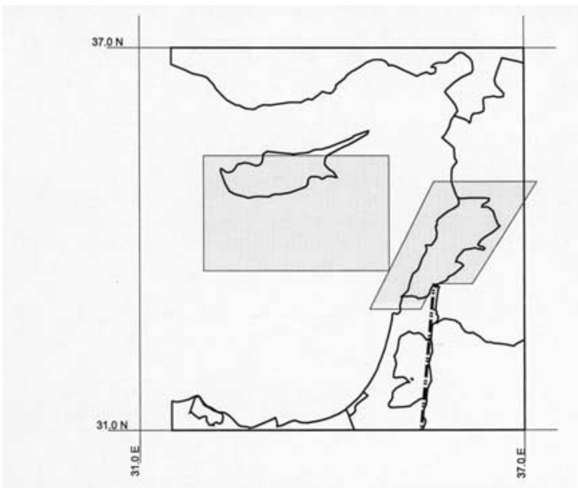


*Figure 8.* Schematic of Model I.

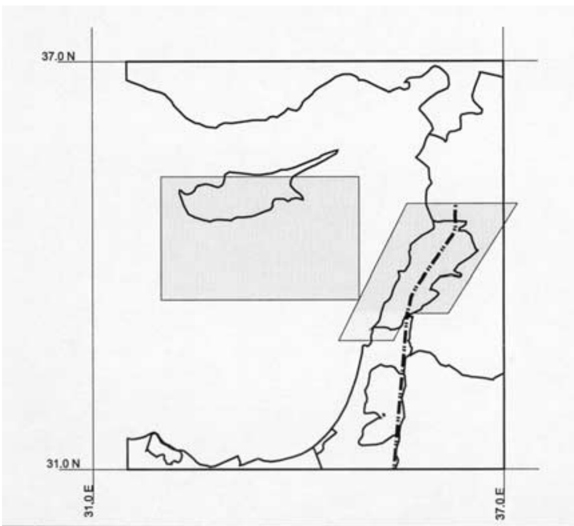


*Figure 9.* Schematic of Model II.

Figure 3, major inland earthquakes ($M > 6.0$), including the maximum earthquake of magnitude 7.5, strike predominantly, and with equal probability, along the 150 km long *Yammouneh* fault line.

This restriction imposed on the location of large magnitude earthquakes is compatible with the concept of seismic locking of the *Yammouneh* fault (Nur and Ben-Avraham, 1978; Walley, 1988) and it is consistent with the historical earthquake data presented in Figure 6. In mathematical terms, when used in conjunction with seismic hazard analysis, it is similar, in some respect, to the use of distance probability distribution functions (Der-Kiureghian and Ang, 1977), which are employed when earthquakes are more likely to occur along some parts of the seismic source than along others.

Based on the assumptions above, the seismic source for the Lebanese segment becomes equivalent to an area source defined in Figure 3 (area = 25,000 sq.km) with maximum magnitude equal to 6.0 plus a line source along the *Yammouneh* fault line (length = 150 km) with earthquake magnitudes between 6.0 and 7.5, both of which have a rate of recurrence of earthquake events as described in Eq. (15).

As in the case of model I, the analyses based on model II, involve the contributions of the Lebanon region as described above (area plus line source), in addition to the contribution from the Southern section of the Dead Sea fault system and the Mediterranean region both defined earlier.

The seismic sources proposed in models I and II above and the earthquake recurrence relationship developed are believed to be the most realistic for evaluating the seismic hazard of Lebanon given the fact that they are to a large extent consistent with experts opinions as far as the tectonics and seismicity of the region are concerned.

## Attenuation relationship

Due to the fact that data for moderate and strong earthquake records are unavailable, no instrumental data-based relationship has yet been developed to describe the attenuation of ground motion in this part of the world. Therefore, it was necessary to adopt an attenuation relationship from a spectrum of such relations developed worldwide.

In this study, the equation proposed by Ambraseys (Ambraseys, 1995) for Europe relating the peak ground acceleration to the distance from the source of energy release, focal depth, and earthquake magnitude is used (Figure 10). This equation is given as follows:

$$Log(a_h) = -1.06 + 0.245M_w - 0.00045r$$

$$-1.0161Log(r) + 0.25P \quad (16)$$

Where: $r^2 = d^2 + h^2$, d is the source distance in km, h is the focal depth in km, $a_h$ is the median peak horizontal ground acceleration expressed as a multiple of the gravitational acceleration g, $m_s$ is the surface-wave magnitude, and P is 0 for 50-percentile values and 1 for 84-percentile.

It should be pointed out that the sensitivity of the analysis results to the choice of the attenuation relationship was evaluated by considering other relations available in the technical literature as illustrated in subsequent sections.

## Computation procedure

In this study, the lower bound earthquake magnitude ($m_o$) is taken equal to 5.0 for all seismic sources involved in the analysis. Also, it is assumed that the attenuation characteristics of the ground motion are isotropic, that is, they are independent of the location of the site relative to the source of energy release.

The analysis was conducted using the software program, EZ-FRISK, developed in 1998 by Risk Engineering, Inc – Boulder, Colorado, U.S., which is an extension of previous similar programs developed by McGuire (1978). The program has the capability of handling combinations of seismic sources and multiple attenuation equations and has the advantage of calculating the hazard accurately and efficiently for a wide range of assumptions that are now common in seismic hazard analysis. For the purpose of this study, the region under investigation was divided using approximately a 10 by 10 km mesh, with a total of about 270 different locations of mesh nodal points. The output of the analysis includes the average return periods for 10 different peak ground accelerations varying between 0.05 g and 0.5 g, the probability that these ground accelerations are exceeded in 50, 100, and 500 years exposure time, and the ground accelerations corresponding to 0.1 probability of exceedance in 50, 100, and 500 years.

## Results of the hazard analysis

### *Ground acceleration maps*

Results of the seismic hazard evaluation showing contour lines of peak ground acceleration (PGA) corresponding to 0.1 probability of exceedance in 50 years and 100 years (return period of 475 and 950 years, respectively) for the two seismic source models used in the Lebanese segment are shown in the maps of Figs. 11 through 16. The variation of the PGA with the probability of exceedance for the Capital City Beirut for 50, 100 and 500 years exposure time, obtained using model II, is shown in Figure 17.

It can be observed from Figure 11 that for 50 years exposure time (return period of 475 years), the maximum PGA obtained using model I does not exceed

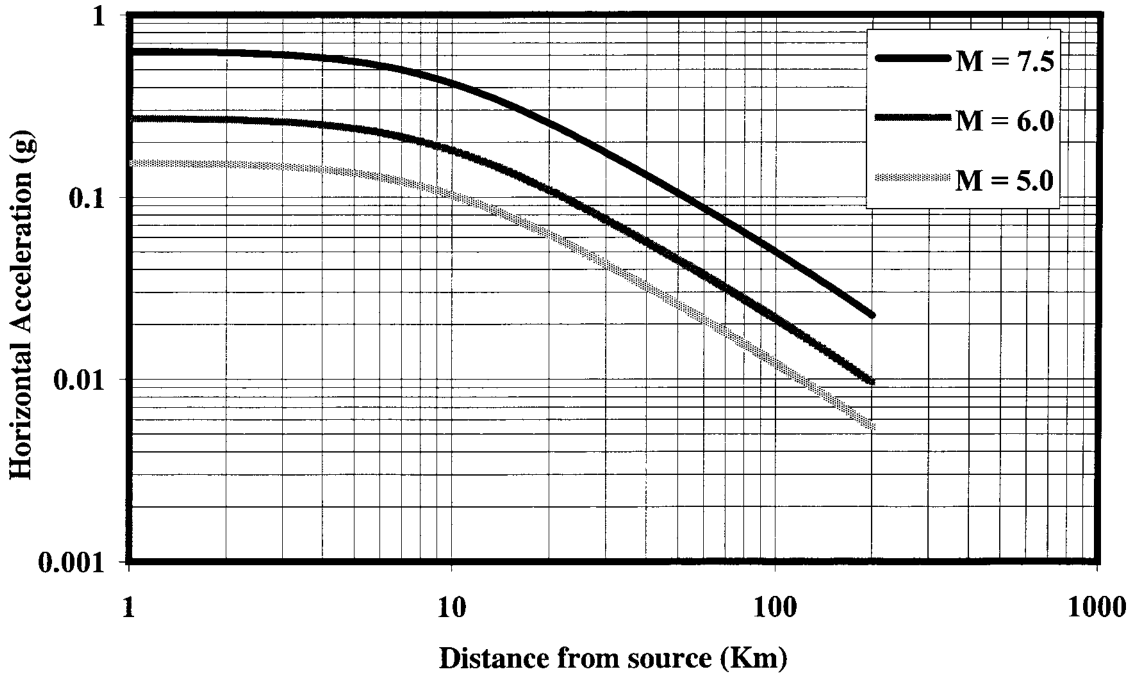


*Figure 10.* Attenuation relationships used in the analyses.

0.15 g almost across the entire Lebanese territory. On the other hand, using model II for the same exposure time, the PGA varies between 0.2g along the eastern and western boundaries to a maximum of approx 0.35g in the Bekaa plateau close to the *Yammouneh* fault line for both $m_u = 7.5$ and $m_u = 7.0$ (Figures 12 and 13 respectively). Note that the limits of PGA obtained in both models for the coastal region, which is the most heavily populated area in Lebanon (constitutes more than 75 percent of the Lebanon population) are normally those that designate regions of moderate seismic hazard. Also, it can be observed in Figs. 14, 15 and 16 that the PGA having 10% probability of exceedance in 100 years is about 33 percent larger compared to that for 50 years.

Figure 17 shows that as the time span increases, the peak ground acceleration for a selected level of probability of exceedance increases as would be expected. For instance, the PGA for the capital city Beirut corresponding to 10 *percent* probability of exceedance for exposure times of 100 and 500 years is approximately equal to 1.3 times and 1.7 times that for 50 years respectively. Sensitivity of the results as to variations in standard deviation is also investigated and presented in Figure 17.

*Effect of the attenuation relationship*

The sensitivity of the hazard analysis results to the choice of the attenuation relationship was explored by comparing results obtained using the attenuation relationship adopted in this study (Eq. 16) with those obtained using the relationship proposed by Campbell and Bozorgnia (1994), which is derived using worldwide records of earthquakes with moment magnitude between 4.7 and 8.1. For the nature of the fault system (strike-slip faulting) and the geological conditions in Lebanon, the relationship takes the following form:

$$Ln(y) = -3.512 + 0.904M_w$$

$$-1.328Ln\sqrt{R^2 + [0.149e^{0.647M_w}]^2}$$

$$+0.440 - 0.171LnR + \sigma \qquad (17)$$

In which y is the median peak horizontal ground acceleration expressed as a multiple of the gravitational acceleration g; R is the closest distance to the sur-

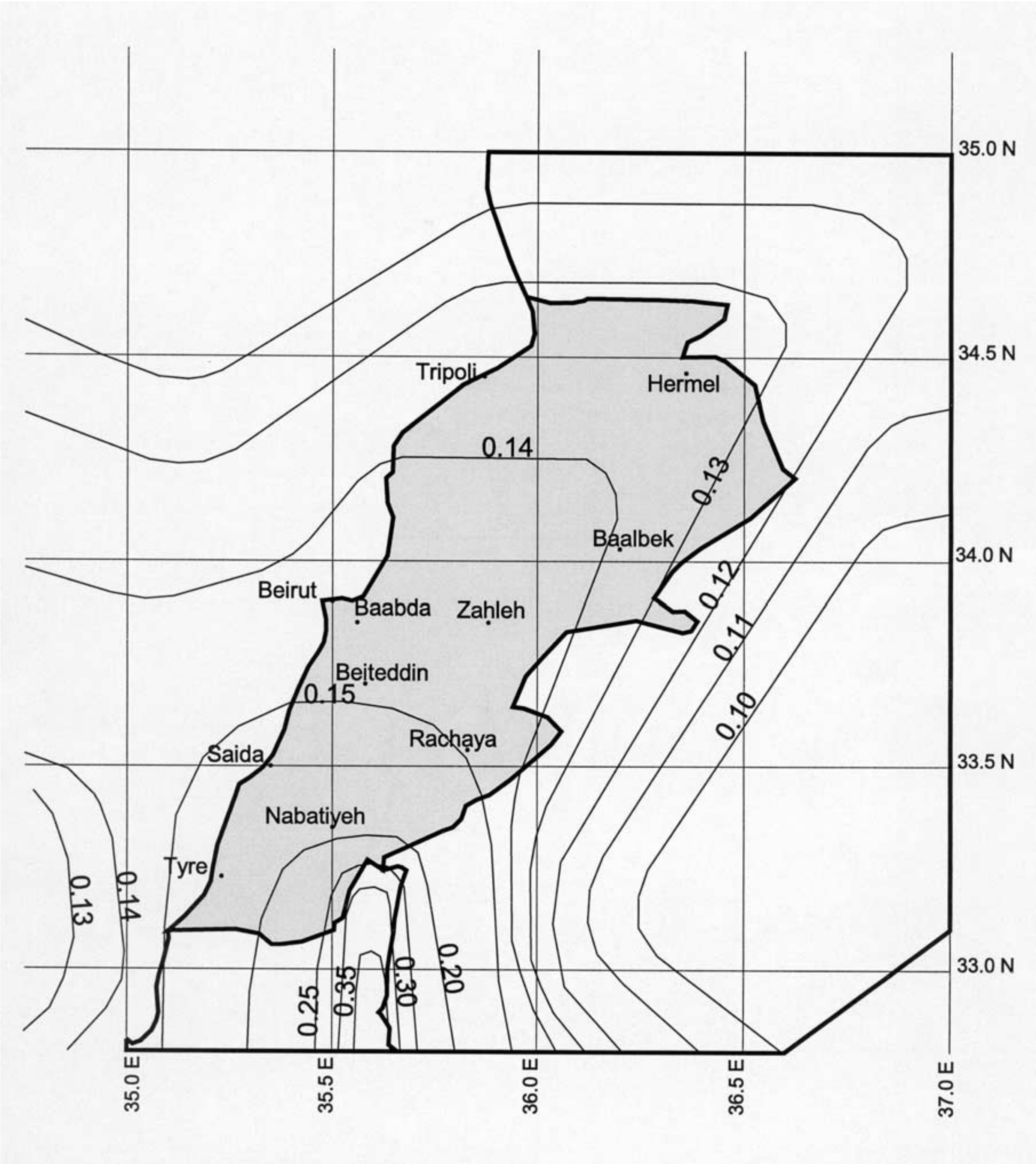


*Figure 11.* Contour lines of peak ground acceleration for 0.1 probability of exceedance in 50 years using seismic source model I with $m_u = 7.5$.

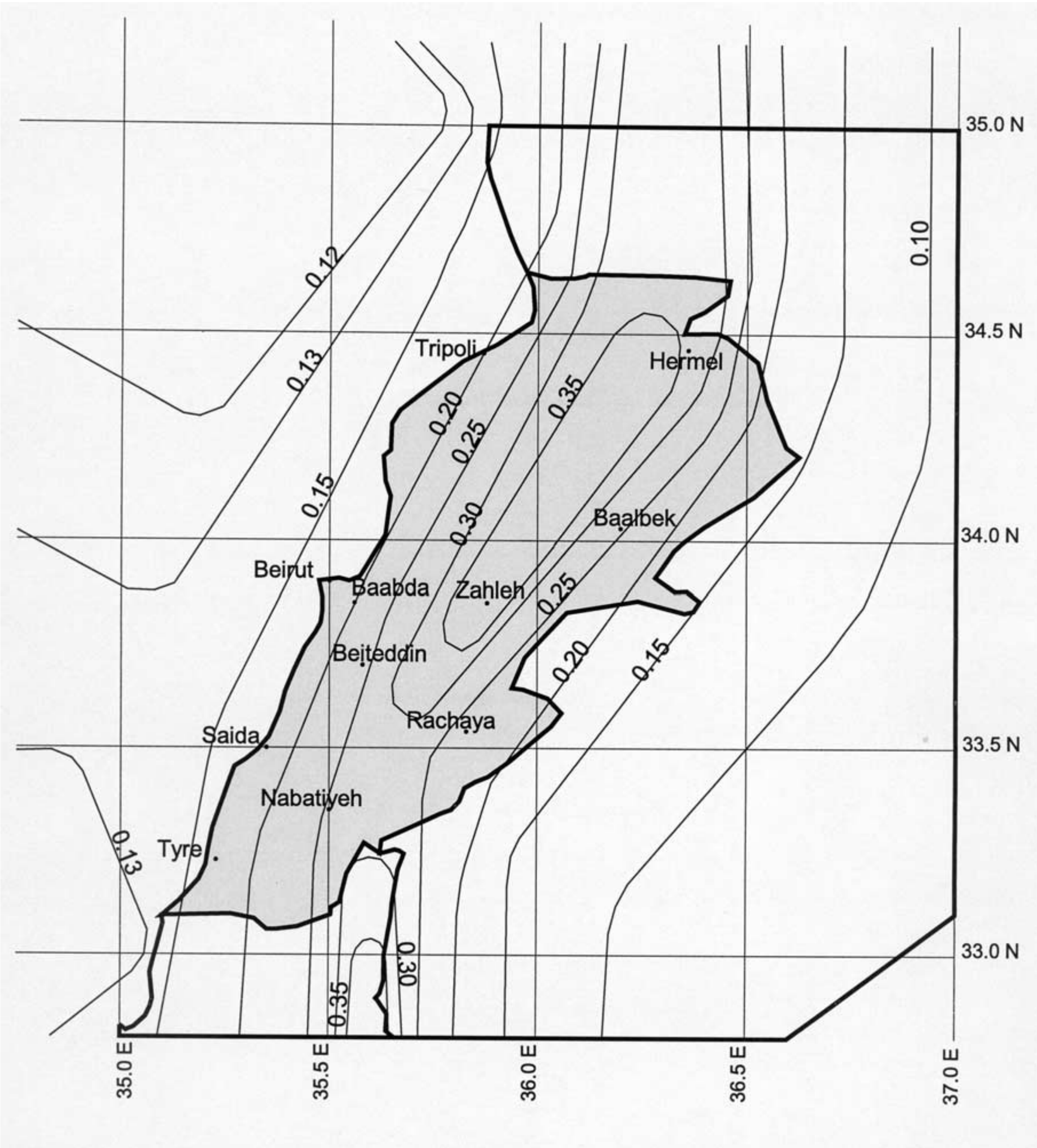


*Figure 12.* Contour lines of peak ground acceleration for 0.1 probability of exceedance in 50 years using seismic source model II with $m_u = 7.5$.

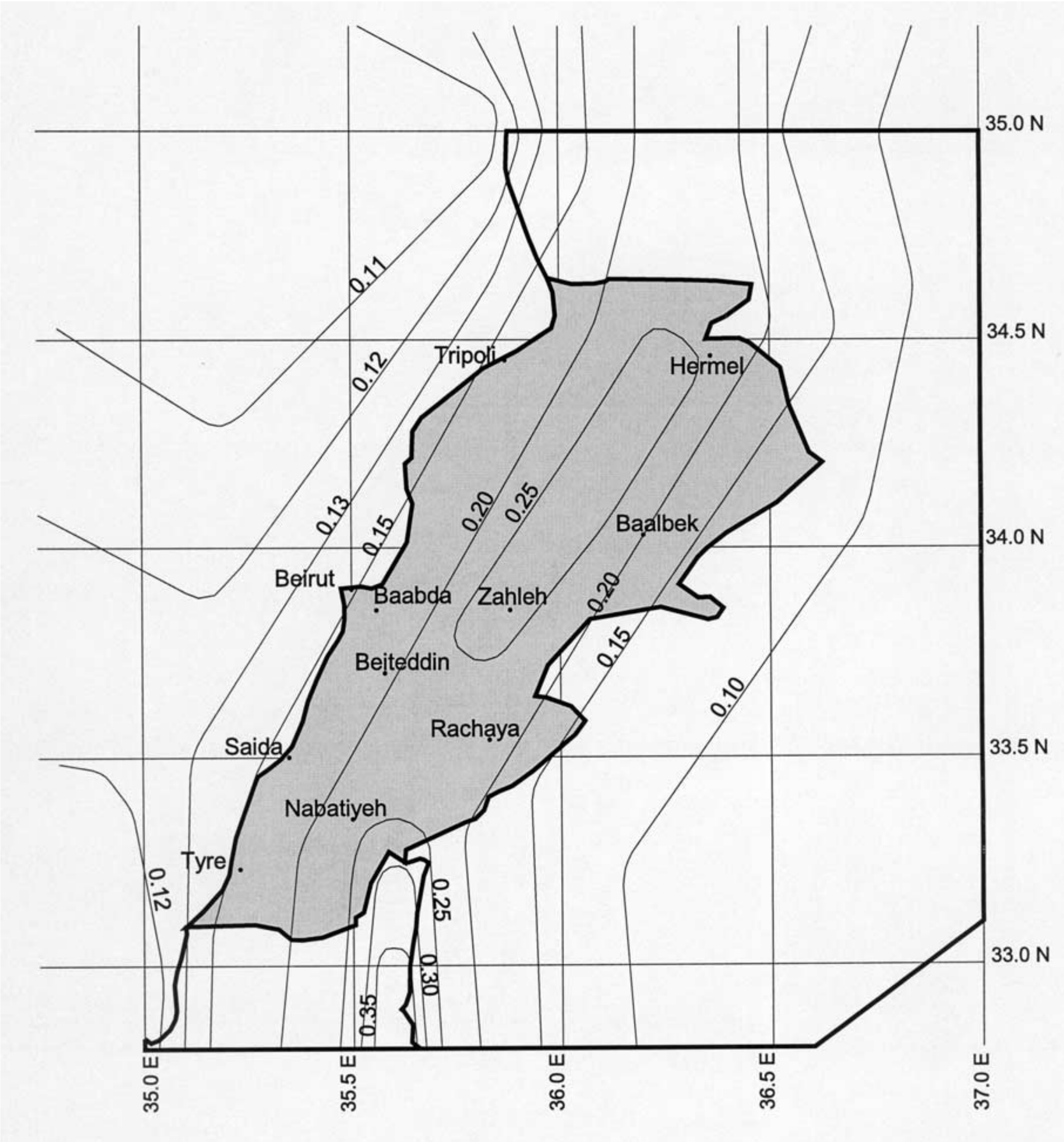


*Figure 13.* Contour lines of peak ground acceleration for 0.1 probability of exceedance in 50 years using seismic source model II with $m_u = 7.0$.

face projection of the source; and $m_w$ is the moment magnitude. The standard error term $\sigma$ in Eq. 17 is magnitude dependent and is taken equal to 0.889 – 0.0691$M$ for $m \leq 7.4$, and constant (equal to 0.38) for $m > 7.4$.

Results of hazard evaluation using the attenuation equation above in comparison with the equation adopted in this study, obtained using model II, is shown for the City of Beirut in Figure 18. It can be seen in this figure that the ground accelerations are almost identical for return periods less than about 500 years (Eq. 17 being less conservative) but the difference in the results increases with increasing return periods. This supports the observation made by Idriss (1985)

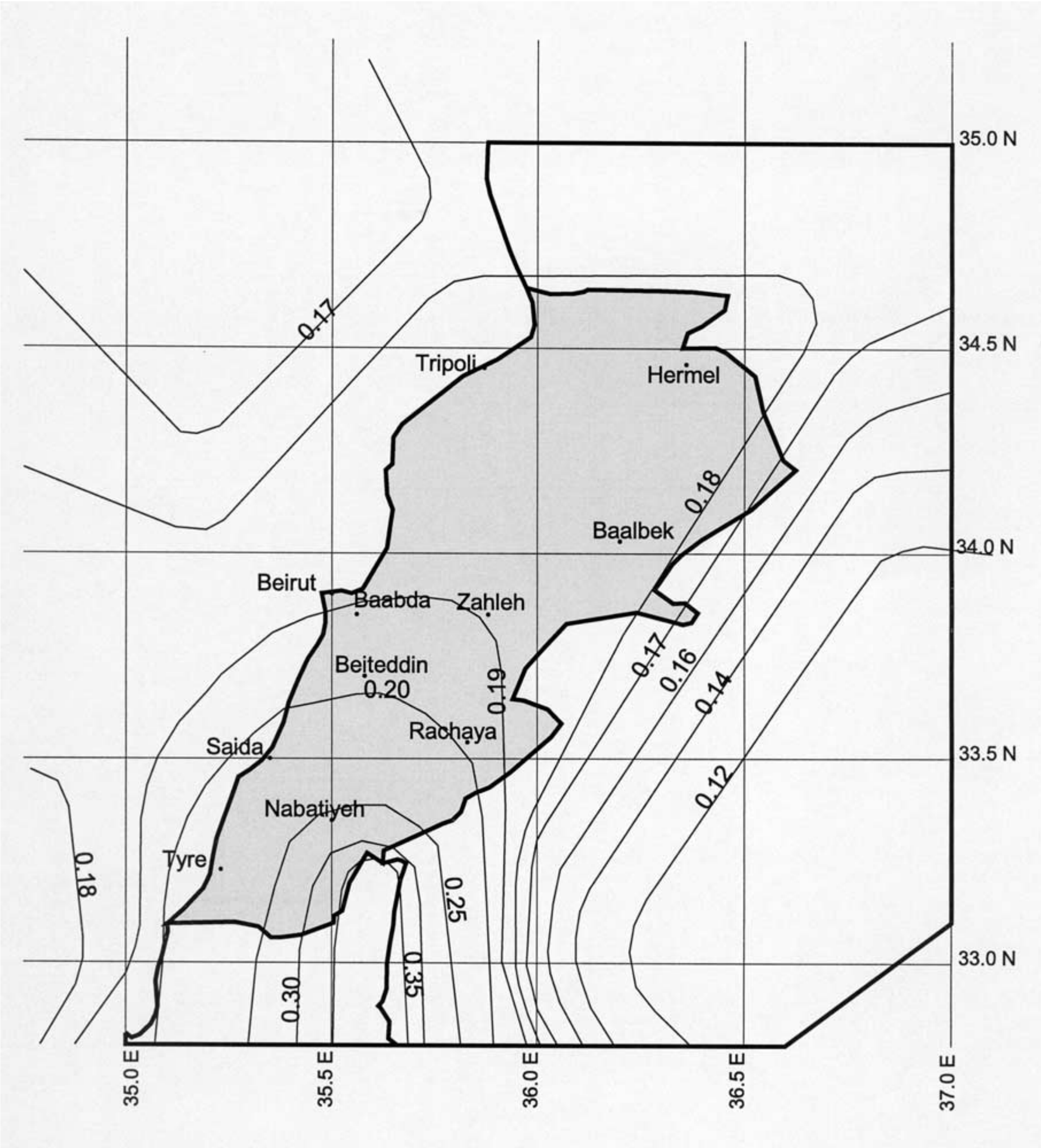


*Figure 14.* Contour lines of peak ground acceleration for 0.1 probability of exceedance in 100 years using seismic source model I with $m_u = 7.5$.

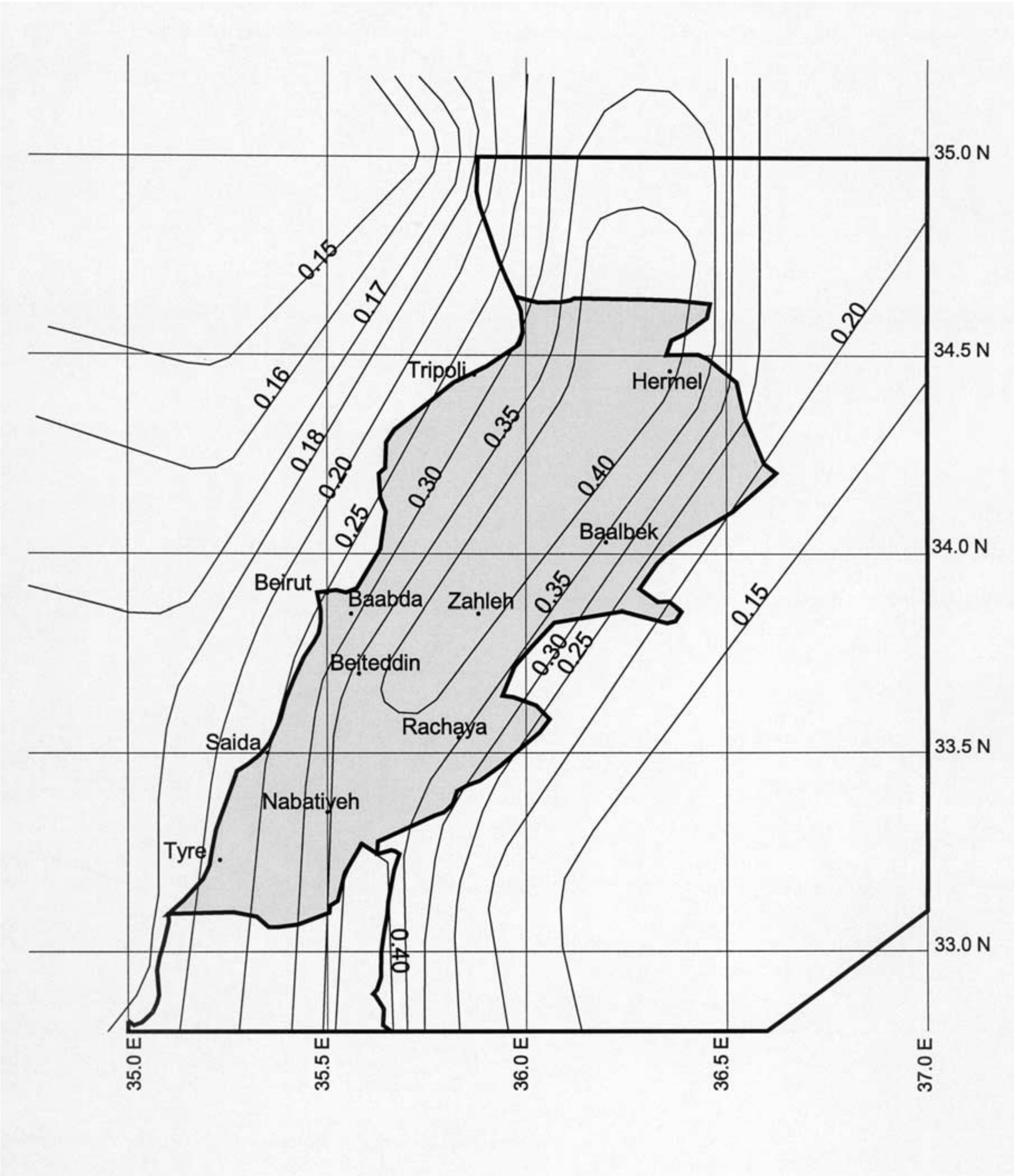


*Figure 15.* Contour lines of peak ground acceleration for 0.1 probability of exceedance in 100 years using seismic source model II with $m_u = 7.5$.

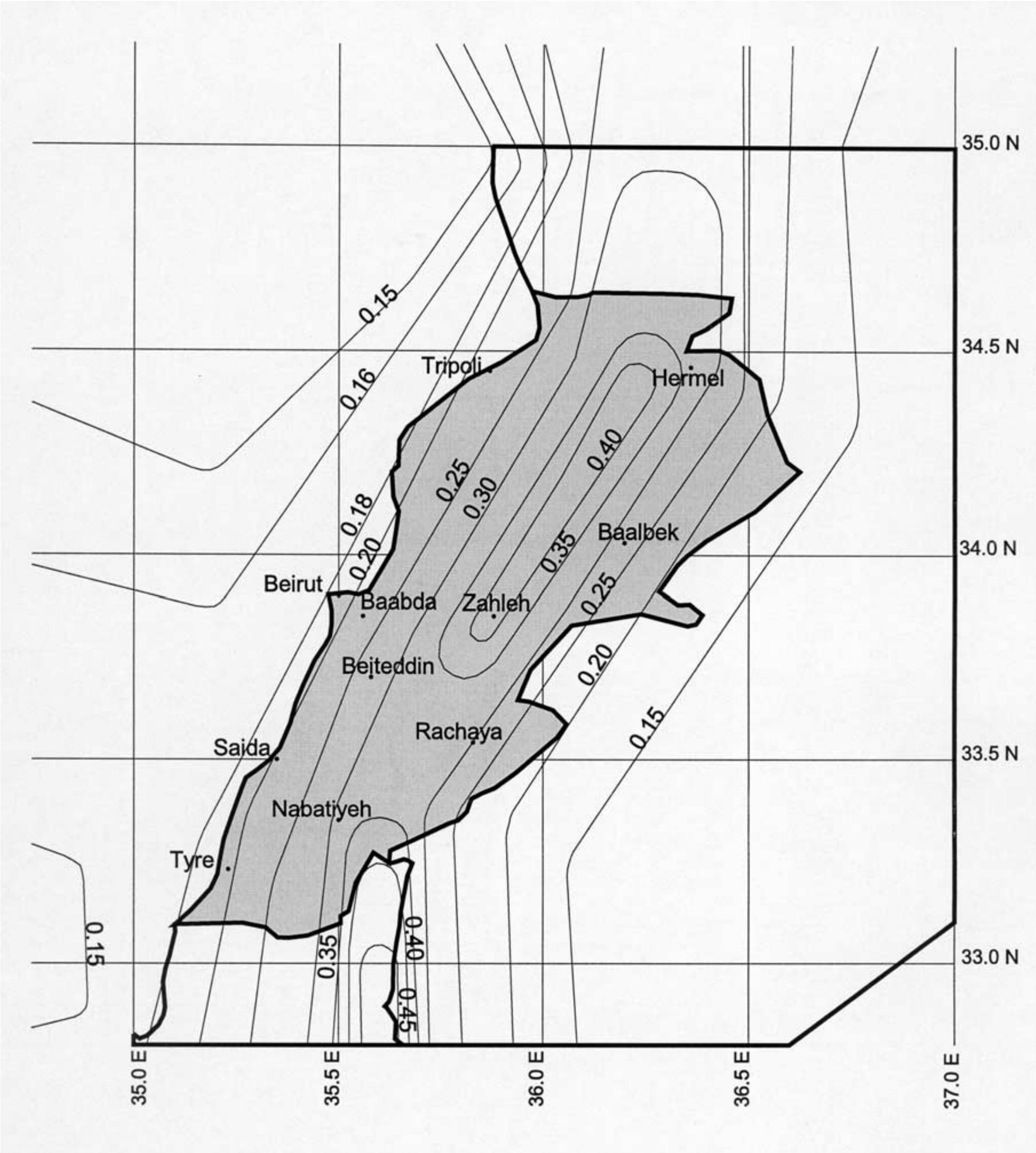


*Figure 16.* Contour lines of peak ground acceleration for 0.1 probability of exceedance in 100 years using seismic source model II with $m_u = 7.0$.

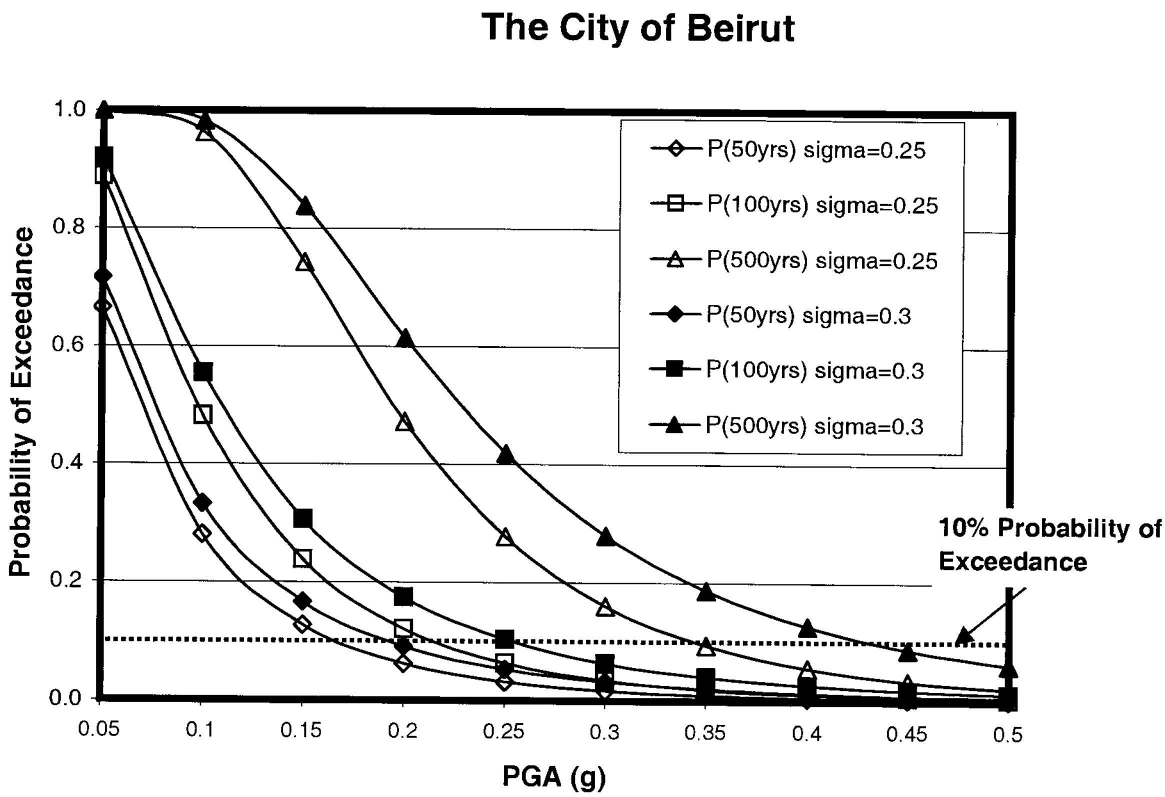


*Figure 17.* Variation of probability of exceedance versus peak ground acceleration for Beirut,using seismic source model II.

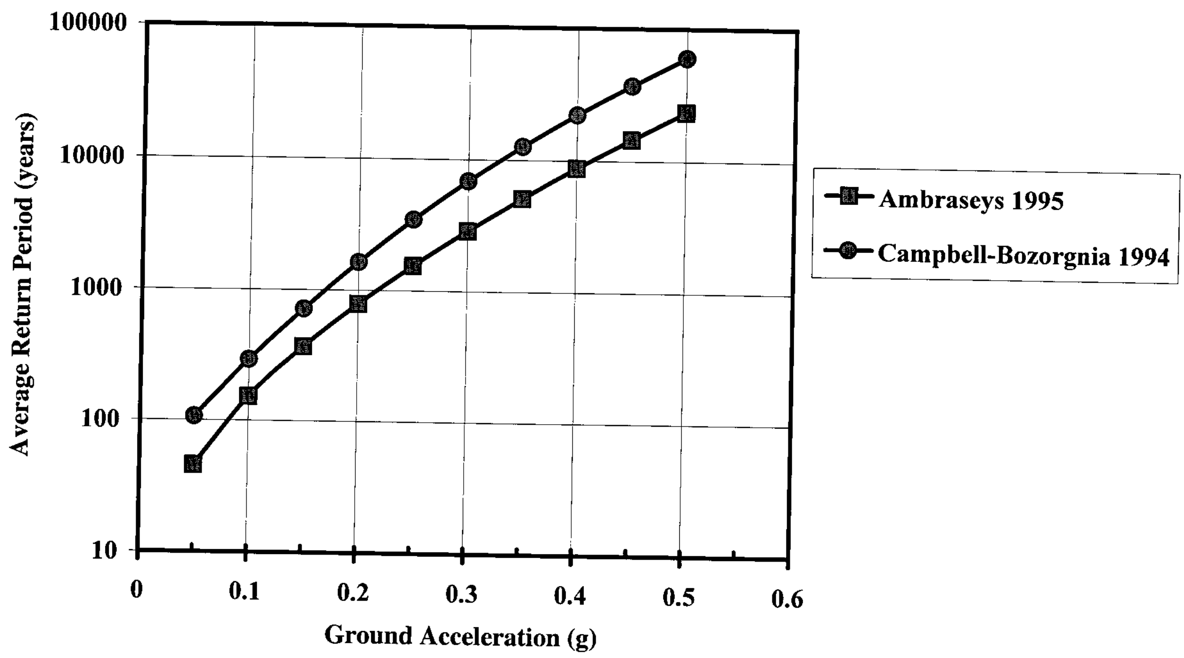


*Figure 18.* Influence of the attenuation relationship on the seismic hazard results for Beirut.


*Figure 19.* Proposed seismic zonation map for Lebanon.

that for relatively small return periods, the attenuation equation does not appear to have much influence on the results of hazard analyses.

## Proposed seismic zoning map

Based on the results of this investigation, it would be possible to zone Lebanon into two zones of seismic hazard corresponding to 10 *percent* probability of exceedance in 50 years (Figure 19): One zone along the eastern and western territories with effective PGA equal to 0.2 g, where g is the gravitational acceleration. The second zone is parallel to the *Yammouneh* fault line within about 15 kms distance on either side of the fault, and having effective PGA equal to 0.3 g. These correspond respectively to zones 2 and 3 of the Uniform Building Code UBC 94 of the United States. Note that most of Lebanon's population (about 75 percent) and capital investments are located on the country's west coast.

The recommended ground accelerations above are the minimum that should be used in seismic design and may be taken conservatively as the ground acceleration on rock. The final design acceleration may be amplified depending on the type of soil overlying the bedrock, and the dynamic characteristics of the structure. Classification of soils in Lebanon with regard to their influence on the dynamic response under earthquake loading were covered in detail elsewhere (Harajli et al., 1994.)

## Summary and conclusions

This study concentrated on the evaluation of the seismic hazard of Lebanon to determine the most probable ground acceleration needed for seismic design. The seismic hazard evaluation was conducted using available methods of probabilistic seismic hazard analysis. The analysis required the generation of historical and instrumental earthquake database (epicenters, magnitudes), the modeling of seismic sources and development of their earthquake recurrence relationships, and the use of ground acceleration attenuation relationship. Because geological studies addressing the issue were not available, it was necessary to rely on historical records to determine the maximum magnitude earthquakes that the fault system in Lebanon can produce and estimate their recurrence period. The sensitivity of the results to the use of different seismic source models in the Lebanese segment, and the choice of the attenuation relationships was evaluated.

Based on the results of this study, the following conclusions are drawn:

1. Lebanon is a country of moderate to high seismic hazard. The peak ground acceleration corresponding to 10 *percent* probability of exceedance in 50 years exposure time for most areas within Lebanon varies between 15 and 35 *percent* of the gravitational acceleration.
2. For the purpose of seismic design, Lebanon can be zoned into two regions of seismic hazard: Zone I – moderate seismic hazard, with effective ground acceleration equal to 20 percent of the gravitational acceleration g, and Zone II – high seismic hazard, having effective ground acceleration equal to 30 percent of g. Zone I covers the eastern flanks and the west coastal zone where most of the population and capital investment fall. Zone II covers the central part of Lebanon from the far north to the far south within 30 km wide region parallel to the Yammouneh fault line.

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