Chapter VII

Geographic distribution of earthquakes in the Maghreb

1. Introduction

The previous chapters present the methodology used in collecting and analyzing both macroseismic and instrumental data about earthquakes in the Maghreb region. From the sources available, a total number of 7724 earthquakes, of which 2061 have a surface-wave magnitude equal to or greater than 3.0 which is presented in Appendix A, spanning the 91-year period 1900-1990, have been identified and are contained in the catalogue (to be published separately). Figure 1 shows a plot of the cumulative time distribution of all the reported events in the Maghreb this century. This figure exhibits a certain uniformity in the cumulative time distribution of earthquakes reported between 1930-1990. In the early years of instrumentation 1900-1930, the number of events reported increased considerably during 1901-1910. It increased also, but at a lower degree, in the period 1911-1920 and again at a lower rate in 1921-1930. The effects of World War Two on the reporting of earthquakes in the Maghreb can easily be seen during the time period 1939-1950 and which resulted in lowering the level of reports.

The spatial distribution of earthquakes in a particular region characterizes its tectonic and geologic structure and activity. Thus, epicentral maps, depending on the accuracy of the hypocentre locations, may be used for a seismotectonic interpretation in the region, *i.e.*, the identification of tectonic features with which the seismic activity of the region is associated, as well as for the geologic structure. They are also used to delineate the earthquake source zones and thus to evaluate seismic hazard and risk in the region.

The seismicity in the Maghreb is analyzed by examining the distribution of epicentres, focal depths, which remain the most uncertain of hypocentral coordinates, magnitude-frequency relationships and the seismic strain distribution over the twentieth century. It is of interest to mention that, according to the study of the seismic strain in the Atlas, it was found that the 91-year time (1900-1990) of observations is too short to be representative of longer periods of the seismic activity in the Atlas zone.

2. Regional setting

The Maghreb region has a relatively moderate seismicity despite the apparent tectonic activity of that thrust zone of 2300 km long and 400 km wide. This region, which comprises the Atlas ranges bordering the Western Mediterranean Sea and the Southern Iberic peninsula, has experienced, since hundred million years ago, a common tectonic evolution characterized by a relative motion between the left and right lateral along the African and Eurasian plates (Patriat *et al.*, 1982). Figure 2 shows the convergence motion between the African and Euroasian plates, after Patriat

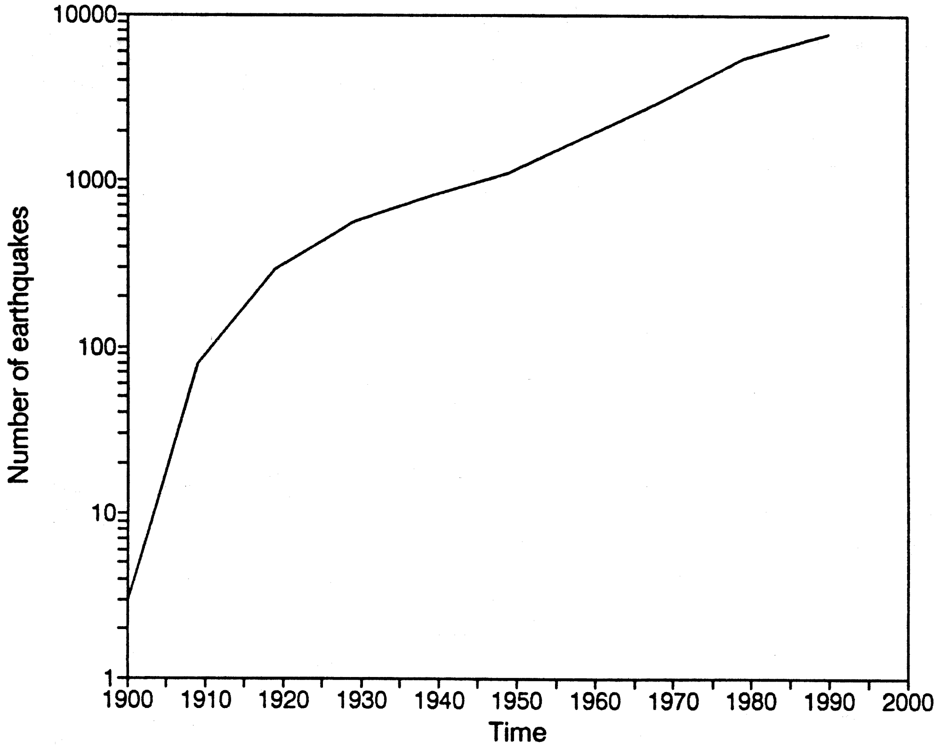


Fig. 1. Cumulative time distribution of number of earthquakes reported in the Maghreb during the period 1900-1990.

et al. (1982). Because the region is not in a subduction zone, it may be considered that the corresponding deformations due to plate convergence are concentrated to a great extent in the North African mountains, which exhibit many characteristics of plate collision tectonics. Recent tectonic studies of McKenzie (1972), Dewey *et al.* (1973), Alvarez *et al.* (1974), Tapponnier (1977), Groupe de Recherche Neotectonic de l'Arc de Gibraltar (1977), Hatzfeld (1978), Patriat *et al.* (1982) and Philip and Meghraoui (1983) have shown that the recent collision between the African and Euroasian plates mainly produced compressive tectonics where thrust and strike-slip deformations are associated. Figure 3 shows the focal mechanisms, fault traces, as well as directions of maximum compression, in the Iberian-Maghreb region, after Philip and Cisternas (1985). These deformations show a main NNW-SSE shortening direction. In this work, the average uplift rate was computed at 1.76 mm/year and the shortening rate as 1.48 mm/year for the whole Atlas ranges. However, some extensional surface ruptures, perpendicular to the compressive direction, may appear locally, as in El-Asnam 1980 earthquake (Ambraseys, 1981; Philip and Meghraoui, 1983).

In examining the epicentral map (see map 1, Chapter V), it can clearly be seen that most of the seismic activity in North Africa is concentrated along the Atlas mountains. These mountains form a geological section distinct from the rest of the continent. The Atlas section, which spreads out from Agadir in Southwest Morocco, crossing Northern Algeria, to the gulf of Gabes in Tunisia, is delimited by the Mediterranean Sea in the north and the east, the Saharan desert in the south and by the Atlantic Ocean in the west. The Atlas block is constituted by two main chains separated by High Plateaux: the Tell Atlas and the Saharan Atlas. The Tell Atlas consists of a succession of mountain ranges, plateaux and valleys, with the principal direction of the relief roughly parallel to the

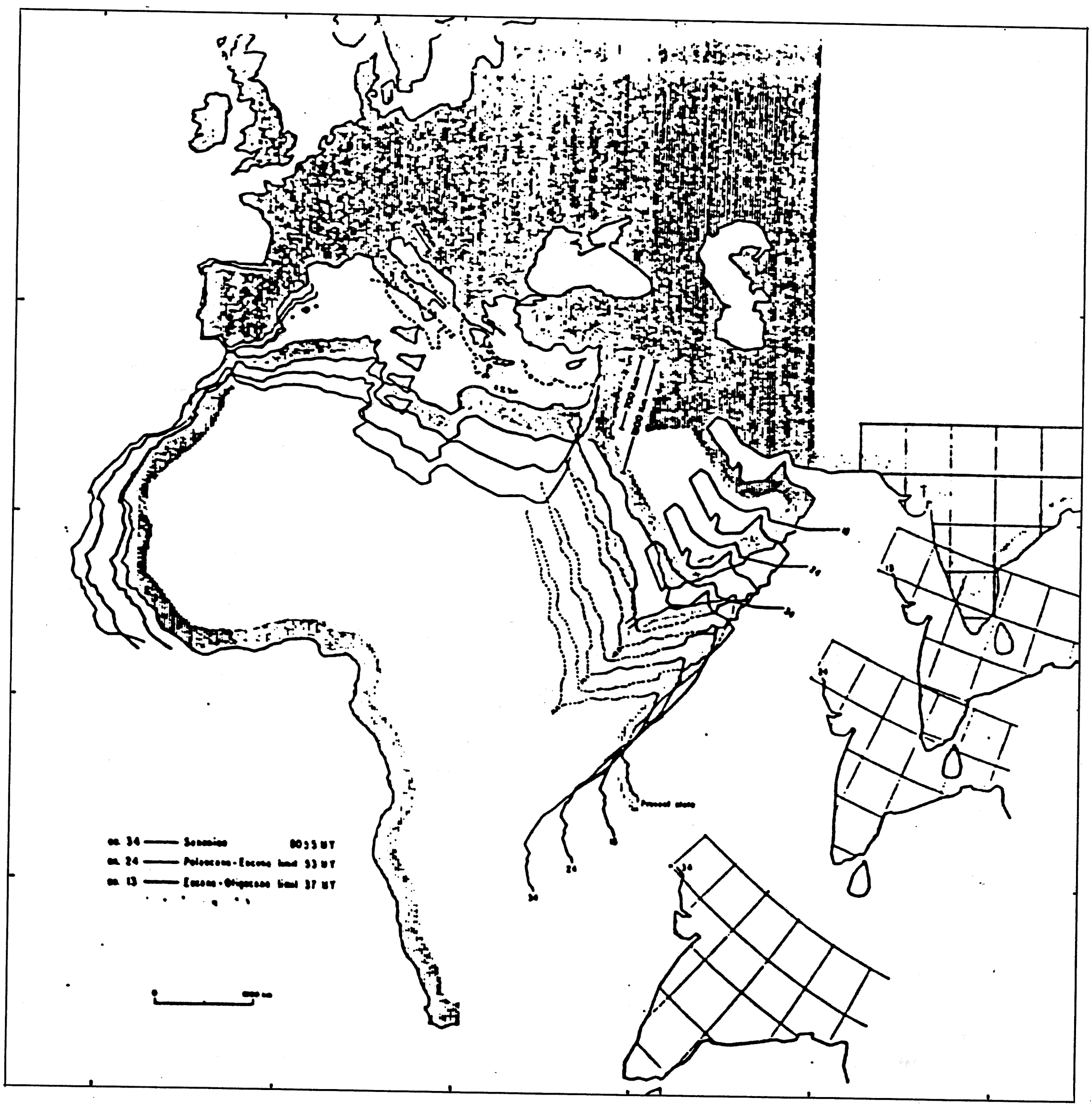


Fig. 2. Plate tectonic motions between the African and Eurasian plates (after Patriat *et al.*, 1982).

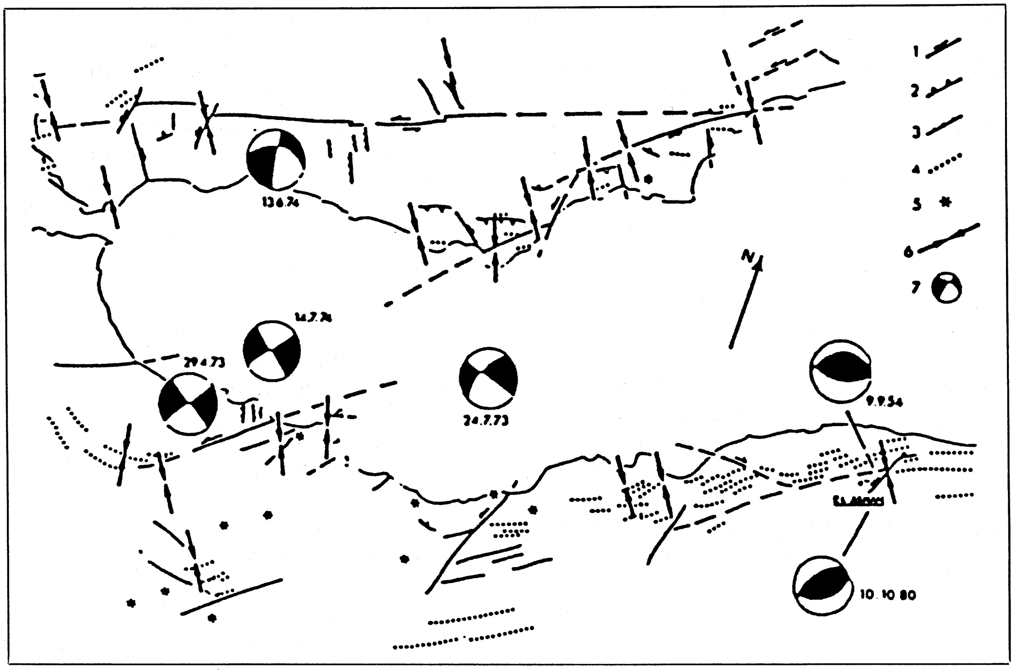


Fig. 3. Seismotectonic map of the Western Atlas and Southern Spain showing focal mechanisms, fault traces and directions of maximum compression (after Philip and Cisternas, 1985). 1) Strike slip; 2) thrust fault; 3) normal fault; 4) quaternary fold axis; 5) alkaline volcanism (age = 3 Ma); 6) direction of maximum compression; 7) earthquake fault plane solutions.

coastline. Between the Tell Atlas and the Saharan Atlas lies the High Plateaux with its basins of internal drainage (chotts). These two main chains are relatively distinct in Algeria and Morocco, but they join each other progressively and merge into one another in Tunisia where, near Zaghouan, they are separated by a closely vertical fracture. In East Central Algeria, in the Hodna region, these mountains are linked by branches.

From the tectonic point of view, the Atlas block constitutes a section of the Alpine folding axis which extends from the Pyrenées to the Eastern and Western Alps, to the Carpathians, to the Apennines, to the Beatic cordillera and spreads out westward to the Acores. This whole block was uplifted during the Alpine crustal movement which had started by the end of the Jurassic period, recommenced in the upper Cretaceous and continued into the middle and probably upper Miocene. There are also indications of folding during earlier periods with a predominant direction of movement from north to south (Ambraseys, 1962). As a matter of fact, this zone is still subjected to a relatively slow rate of tectonic readjustments which cause light earthquake shocks along the Atlas ranges, except for the Orléansville 1954 and El-Asnam 1980 earthquakes which had been produced by a sudden release of potential energy. The existence of active faults in the zone is very much consistent with the orogenics of the region. Epicentres of earthquake shocks associated with these faults are plotted in the seismic map of the Maghreb (see map 1, Chapter V).

3. Interpretation of the seismic map

The seismic map of the Maghreb has been drawn using the entire compiled earthquake catalogue, including foreshocks and aftershocks, without any selection, altogether 7721 reported events. The spatial distribution of the epicentres of earthquake shocks constitutes a fundamental parameter when studying the seismicity of a particular region, and thus, the seismic hazard and risk.

Taking into consideration the data presented on the seismic map and the information available on the topography, tectonics and on the seismicity of the Maghreb, each country has been divided into different tectonic zones indicating for each one the degree of seismic activity. Algeria has already been divided by geologists into six principal zones (Rothé, 1950, 1952) which can easily be seen on the seismic map (see map 1, Chapter V).

1) The massifs of Great Kabylie, Collo and Edough regions. Actually, these massifs present a certain seismic stability; only epicentres of very light shocks, which may have been mislocated, are observed. It is true that these massifs, as with any coastline zone, could have been taken as epicentres of offshore earthquakes during the early years of this century.

2) The littoral ranges. The examination of the seismic map indicates that this zone constitutes the main seismic lineament in Algeria, by the number of earthquakes felt and recorded. These chains include the Numidique ranges, which continue into Tunisia, the Babors, the Djurdjura, the Blidéen Atlas, massif of Miliana, the Dahra, the Zaccar, Sahels of Alger and Oran, Tessala and Beni Chougrane and Traras, which continue in Morocco. The map also shows a concentration of epicentres at certain regions such as: Oran-Mostaganem (35.7°N-36.0°N, 0.7°W-0.1°E), Tenes-Cheliff Valley (36.3°N-36.7°N, 1.0°E-1.9°), Chenoua mount (36.5°N, 2.5°E), Blidéen Atlas-Sahel of Alger (36.4°N-36.8°N, 2.8°E-3.0°E) and Bejaia-Kherrata (36.5°N-36.8°N, 5.1°E-5.5°E).

3) The interior Tell. Another seismic lineament, which links the Tell Atlas to the Saharan Atlas, includes the Constantine Tell, the Bibans, Titteri, Ouarsenis and the Hodna. The Berrouaghia-Guergour anticline axis, which forms the Bibans, has experienced important earthquakes this century as in Boghar (1925), Aumale (1910, 1923, 1931), Mansoura (1943), Constantine (1908, 1947, 1985), Guelma (1937) and the Hodna (1946, 1960, 1965). It seems that in this zone small earthquakes are less frequent than in the littoral, but strong shocks are violent and destructive (Aumale, 1910; Guelma, 1937; Melouza, 1960; M'Sila, 1965; etc...).

4) The High Plateaux. A zone, between the Tell and Saharan Atlas, with a tabular topography within which no earthquake has been recorded so far, except very few light shocks appearing in the seismic map, which may have been mislocated by the ISS. Montessus de Ballore (1906) had already observed the seismic stability of this zone.

5) The Saharan Atlas. These mountains comprise the Medjerda, which join the Tell Atlas in Tunisia, Aures, Ouled Nail, Djebel Amour and Ksours Mount, which continue in the Moroccan Atlas. This zone is characterized by a low seismic activity; the important events were severe and concentrated in certain sites such as Aures (Mac-Mahon, 1924), Ouled Nail (Bou Saada, 1929; Djelfa, 1940) and Ksours Mount (Geryville, 1948). Some of these earthquakes may have been strong enough to cause damage to property and loss of lives (Mac-Mahon, 1924).

6) The Sahara. Very few earthquakes are reported in this vast zone and no seismic lineament can be clearly observed. The absence of seismograph stations before 1948, the very low population density and the type of construction, made impossible the survival of earthquake information in the region. However, the ISS had located only two events in the Sahara (see Maghreb catalogue) before the installation of the

Tamanrasset seismograph station. The whole region was considered aseismic until the installation of the seismograph station in 1948 at Tamanrasset. Since then, a certain seismic activity has been recorded. It was on 10 January 1957 that, for the first time in Hoggar history, an earthquake was felt by the population between Ideles and Garet El Djenoun. This earthquake has been recorded at the Tamanrasset seismograph station and located at 25.0°N, 5.40°E (ISS), for which Ambraseys and Adams (1986) have assigned a surface-wave magnitude at 4.4 and maximum intensity at V (MSK). Another shock was felt by the inhabitants on 5 July 1957 and confirmed at the seismograph station. A surface-wave magnitude at 4.1 and maximum intensity at IV (MSK) have been attributed by Ambraseys *et al.* (1986) to this earthquake which was located at 22.8°N, 4.7°E (ISS). To give an idea of the degree of the seismic activity, it is noteworthy that during the period 1948-1958, 48 shocks were recorded at the seismograph station at Tamanrasset as reported by Benhallou (1985) who used Grandjean (1960) as his sources. A small number of earthquakes, generally not felt by the inhabitants, are recorded each year at the station which confirms the low seismic activity in this zone. Only nine events have been located in the Algerian part of the Sahara since the beginning of the century. As a result of this brief analysis, it may be concluded that, in general, the Algerian earthquake epicentres lie out on the main anticline axes.

In examining the western part of the Maghreb region which includes Morocco and the Southern Iberic peninsula, four main zones can easily be distinguished.

1) The zone comprising the Beatic cordillera, the Rif and the Alboran Sea (34.5°N-38.0°N, 2°W-6°W). This zone exhibits the largest concentration of epicentres in the whole Maghreb. It constitutes the Alpine folding axis which continues in the Rif and joins the Beatic cordillera in Southern Spain. From the spatial distribution of epicentres, two main seismic lineaments are clearly discerned; the first one is along the 37°N parallel and the second along the 35°N parallel. Concentration of epicentres can be particularly observed in Malaga, Granada, Motril and Almeria in south Spain and in the Rif at Mellila region.

2) The Atlas zone. This zone constitutes the western branch of the Algerian Atlas mountains. It appears that the geographical distribution of epicentres corresponds to the principal directions of the Atlas ranges. A SW-NE seismic lineament from Taza (34.16°N, 4.01°W) to Tillouguit (32°N, 6°W) forms one of the most seismic areas in the Atlas. Another WSW-ENE seismic lineament joins the Rif to the High Atlas through the Moroccan Meseta. A second concentration of epicentres is observed between Timelloughit (31.6°N, 6.5°W) and Teggour (32.6°N, 4.5°W). A third seismic lineament joining the Saharan Atlas to the south west extremity of the Moroccan Atlas is also observed. Few epicentres are located in the southwestern extremity of this lineament, notably in the regions of Figuig, Ksar Souk and Agadir. This end of the Atlas experienced its worst seismic disaster (M_S = 5.70) on 29 February 1960 which caused the loss of about 12000 lives.

3) The Atlantic zone. This seismic zone is comprised between the Southwest Iberic peninsula, Straits of Gibraltar, Atlantic coast of Morocco and the longitude 10°W which limits the study area. The map shows a seismic lineament linking the Straits of Gibraltar to the Acores along the 36°N parallel which constitutes the western border between the African and Euroasian plates. It is marked by earthquakes of magnitudes larger than VI. A second seismic lineament, not clearly seen, joins SW Cap San Vincente (36.50°N, 10°W) to the Moyen Atlas. Very few epicentres are distributed along the coast. Only two areas around (36.0°N, 9.5°W) and (36.0°N, 8.0°W) exhibit a particular concentration of epicentres.

4) The fourth zone, which consists of the 150 km-wide belt along the southern and southwestern Moroccan border up to the 32.0°N parallel, is considered as aseismic. No earthquake has been reported in this zone during the twentieth century, except two light shocks which, due to the lack of seismograph station in Southern Morocco, may have been mislocated.

In Tunisia, Ambraseys (1962), in a survey of the seismic history, shows that the country has, from an early period of history, experienced frequent small earthquake shocks, and stronger ones at rather longer periods of time. The examination of the seismic map suggests that Tunisia may be divided into two main zones: the seismic north and the aseismic south limited by the 33.5°N parallel.

1) The northern part, comprised between 33.5°N-37.0°N and 8.0°E-12.0°E, has experienced during this century numerous but rather light earthquake shocks. The first seismic lineament is the continuation of the Tell Atlas and Saharan Atlas in Northern Tunisia. Another seismic lineament (the Zaghouan fault) can be seen running from the Gulf of Tunis to Southwestern Tunisia around (33.5°N, 8.0°E). The main concentration of epicentres is observed around the Gulf of Tunis. A third seismic lineament, which is not clearly defined, seems to join the region around (37.0°N, 3.0°E) in Algeria to that around (33.5°N, 8.0°E) in Tunisia.

2) The second main zone consists of the southern part of the country, which is limited to the north by the 33.5°N parallel, and is considered aseismic. No earthquake epicentre has been located in this zone during this century.

The analysis of the seismicity in the Maghreb as a whole suggests that the long return period of relatively strong earthquake shocks in Tunisia and in Southwest Morocco appears to be typical to the orogenics of the two ends of the Atlas mountain ranges. It seems that the crustal readjustments of the two extremes of the Atlas release their potential energy by numerous slight earthquake shocks which draw little attention. In Algeria, the central part of the Atlas, these readjustments are more sudden and sometimes destructive. Except the Orléansville 1954 and El-Asnam 1980 earthquakes, the seismicity of the Maghreb is light to moderate. It is of interest to mention that this analysis is based on the scale of the map only.

4. Distribution of focal depths

Because the Atlas region is in a collision zone, earthquakes occur generally at small depths. The focal depth remains the most uncertain of hypocentral coordinates; its estimation from teleseismic data alone is not precise enough to determine small differences in focal depths of less than 10 km. However, for small and medium magnitude events, particularly aftershocks, focal depths estimates can be adequately computed from local and temporary seismograph networks. Favier *et al.* (1981), Ouyed and Hatzfeld (1981) and Ouyed *et al.* (1982) have shown, in studying more than 500 aftershocks of the El-Asnam 1980 earthquake, that most of the shocks occurred at less than 15 km, among which more than 50 percent were at around 4 km. No attempt was made in this work to determine focal depths. Focal depths reported in the catalogue are those assigned by different authors and agencies. Figure 4 shows a plot of surface-wave magnitude versus focal depth. The examination of fig. 4 reveals the shallow character of the earthquake epicentres in the Maghreb. Among the 1921 events for which focal depth values are available, 1718 earthquakes occurred at a depth less than 33 km, *i.e.* 90 percent of the total number of the events reported this century, and 1836 events (95.5 percent) at depth less than 60 km. Only 85 events (4.5 percent) are reported to have occurred at depths of more than 60 km; this number is very small compared to the total number of

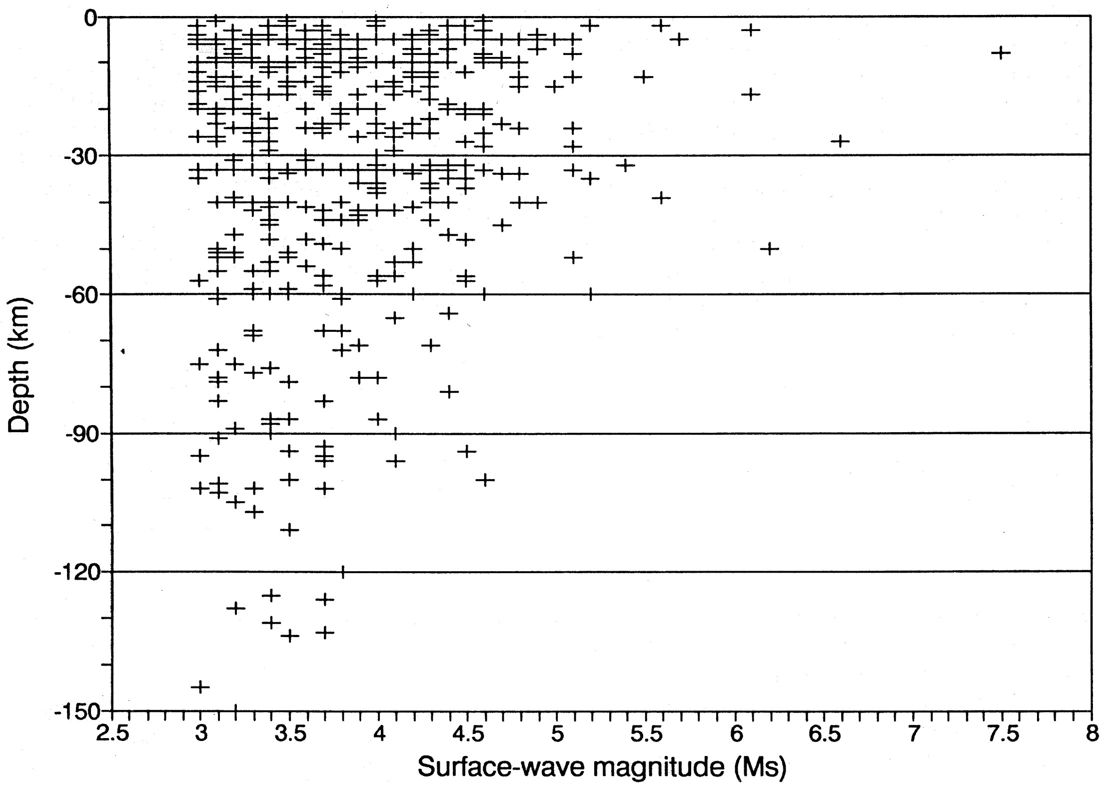


Fig. 4. Plot of depth versus surface-wave magnitude M_S equal to or greater than 3.0 in the Maghreb region.

earthquakes. These intermediate depths are found in the Gulf of Cadix (35.0°N-37.0°N, 6.0°W-9.0°W), west of the Alboran Sea (35.3°N-37.5°N, 2.0°W-5.0°W), the Rif and in the Moroccan Atlas. Only two earthquakes are reported at 603 and 637 km at 37.0°N, 3.5°W. In the Gulf of Cadix, the focal depths are reported between 70 and 120 km. Eighteen intermediate earthquakes, which 15 occurred at depths larger than 100 km, are located in the Moroccan Atlas. There are six intermediate events in the Rif and four in the Southern Iberic peninsula of which focal depths are less than 100 km. In Algeria, 62 percent of the earthquakes with focal depths available are found to have occurred at less than 10 km and 95 percent at less than 33 km. Sixteen events are reported at depths between 33 and 60 km. Only two events of exceptional intermediate depths occurred at 89 km and 95 km respectively at (34.35°N, 2.76°E) and (36.20°N, 2.98°E). In Tunisia, among 186 earthquakes identified, only 56 have had depth values reported. 26 events occurred at depths of less than 12 km, 44 at less than 33 km and 11 occurred at depths between 35 and 79 km. Only one earthquake is reported to have occurred at 103 km on the Algerian-Tunisian border at (36.44°N, 8.18°E). Thus, Tunisia, as Algeria and Morocco, is also characterized by shallow earthquakes.

It should be noted that accurate estimates of depth of focus are fundamental to understand the detailed geologic structure in the Maghreb region. Unfortunately, the accuracy of depth determination, particularly during the pre-1950 period, is low and the study of repartition of hypocentres is obviously incorrect. Therefore, focal depths reported in the catalogue must be considered as approximate. In order to reveal the hidden tectonic features and determine the geologic details of the Maghreb region, hypocentres should be relocated, particularly those before 1950, using present location procedures which are more reliable and accurate.

5. Frequency-magnitude relationships

Considering the recurrence relationships for earthquakes derived by Gutenberg and Richter (1944):

$$\text{Log}\,(N) = a - b\,(M_S) \qquad (5.1)$$

where N is the number of earthquakes exceeding or being equal to a given magnitude M_S in a given region and within a certain period of time, the parameter a describes the seismic activity of the study area (depending on its size and the observed time interval) and b represents the relation between large and small earthquakes. b is assumed to be connected to the tectonic heterogeneity of the area; large values of b are found in areas associated with slow strain rate and vice versa.

For an ideal data sample (including a sufficient number of events) there is only a small difference between the cumulative and single frequency parameters a and b. But when dealing with an incomplete file or not considering the incompleteness of the data samples, the estimates of a and b can be misleading. The cumulative frequency procedure generally shows a better fit, but the resulting values can be highly biased. In this work, in order to reduce the effect of incompleteness, we have determined the time intervals over which the earthquakes of different classes are completely reported in the Maghreb region (see table IV, Chapter V). We may now proceed to estimate the frequency-magnitude relationships in the Maghreb region, the Atlas and in Algeria, using incomplete and complete files, and cumulative frequencies. This constitutes a fundamental phase in the analysis of the seismicity of a given region, since the slope of the recurrence formula, as stated in Chapter V, represents an essential parameter in seismic hazard evaluation. The analysis has been carried out for the main shallow shocks; the foreshocks and aftershocks were removed from the sample.

In applying the linear regression to the different data sets we find the following fits:

1) *The Maghreb region (20°N-38°N, 10°W-12°E)*

a) Incomplete file:

$$\text{Log}\,(N_c) = 6.08 - 0.83\,(M_S) \quad (r = 0.98) \qquad (5.2)$$

b) Complete file:

$$\text{Log}\,(N_c) = 5.96 - 0.82\,(M_S) \quad (r = 0.98) \qquad (5.3)$$

Figures 5a,b show a plot of the cumulative frequency-magnitude relation for the Maghreb region (1900-1990) using incomplete and complete files of shallow earthquakes.

2) *The Atlas mountain region*

a) Incomplete file:

$$\text{Log}\,(N_c) = 5.61 - 0.77\,(M_S) \quad (r = 0.98) \qquad (5.4)$$

b) Complete file:

$$\text{Log}\,(N_c) = 5.53 - 0.76\,(M_S) \quad (r = 0.98) \qquad (5.5)$$

Figures 6a,b show a plot of the cumulative frequency-magnitude relation for the Atlas zone (1900-1990) using incomplete and complete files of shallow earthquakes.

3) *Algeria*

a) Incomplete file:

$$\text{Log}\,(N_c) = 4.79 - 0.67\,(M_S) \quad (\text{r} = 0.97) \qquad (5.6)$$

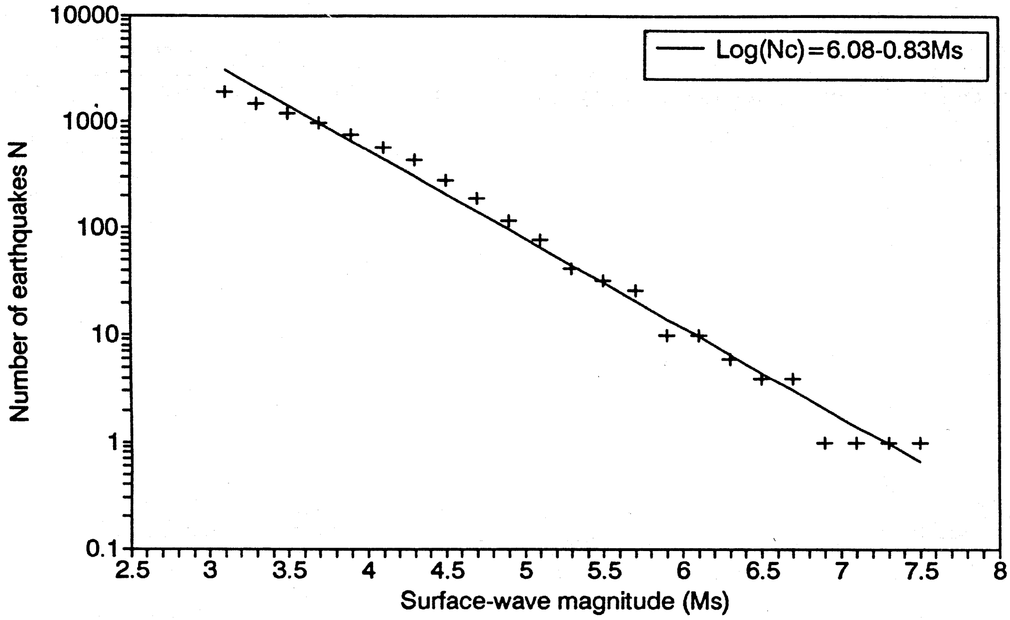


Fig. 5a. Frequency-magnitude relation in the Maghreb region (1900-1990) using incomplete file with $M_S \geq 3.0$.

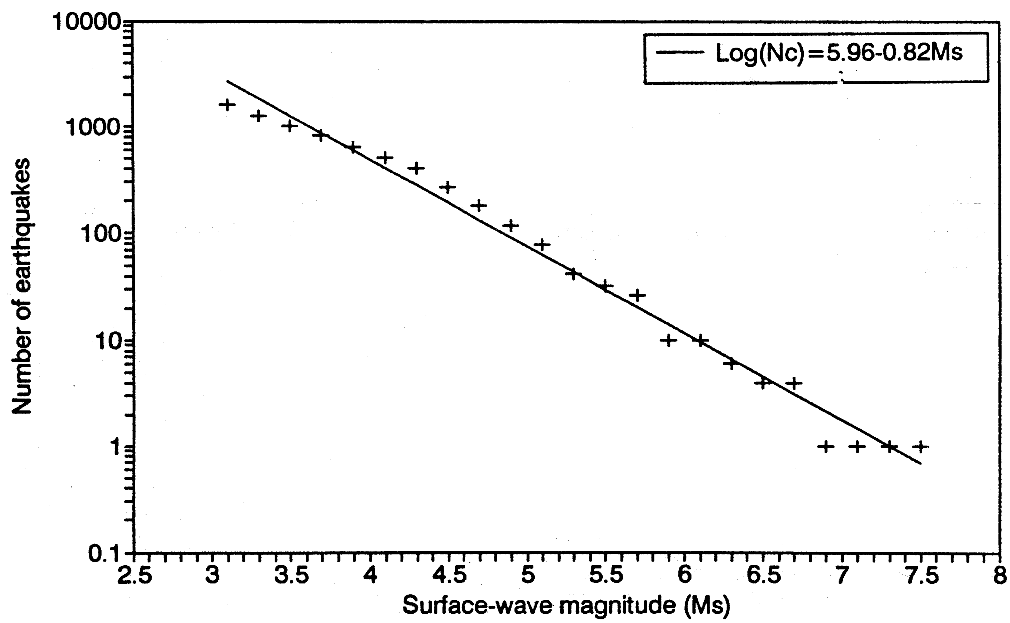


Fig. 5b. Frequency-magnitude relation in the Maghreb region (1900-1990) using complete file with $M_S \geq 3.0$.

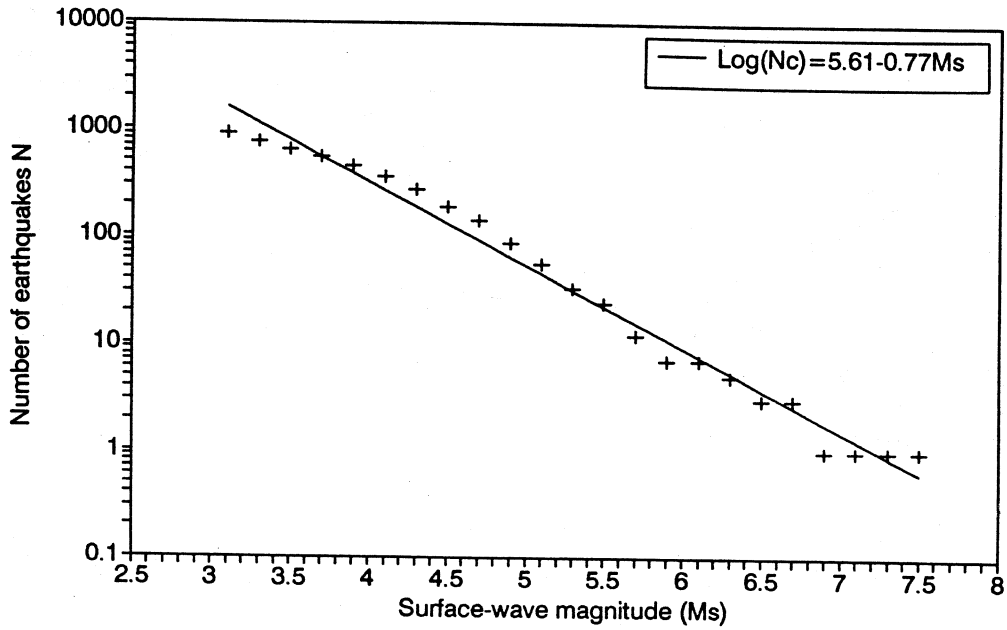


Fig. 6a. Frequency-magnitude relation in the Atlas zone (1900-1990) using incomplete file with $M_S \geq 3.0$.

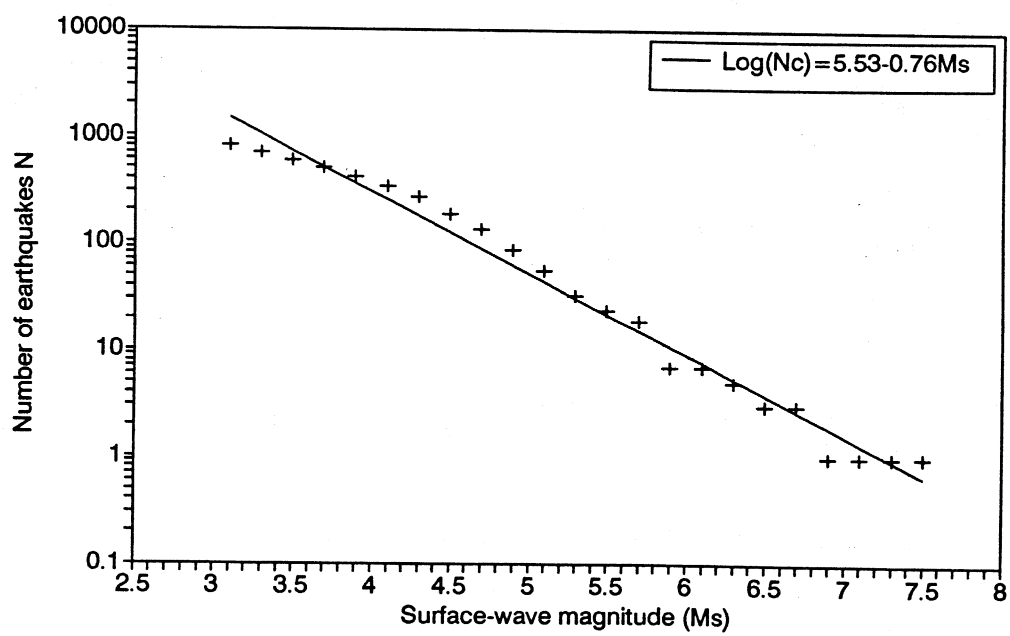


Fig. 6b. Frequency-magnitude relation in the Atlas zone (1900-1990) using complete file with $M_S \geq 3.0$.

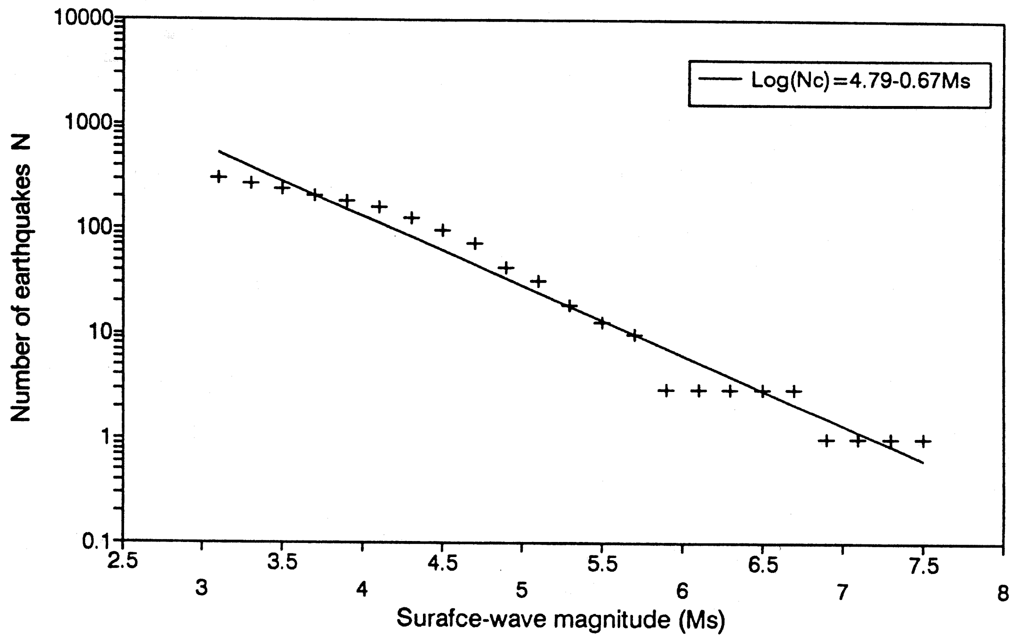


Fig. 7a. Frequency-magnitude relation in Algeria (1900-1990) using incomplete file with $M_S \geq 3.0$.

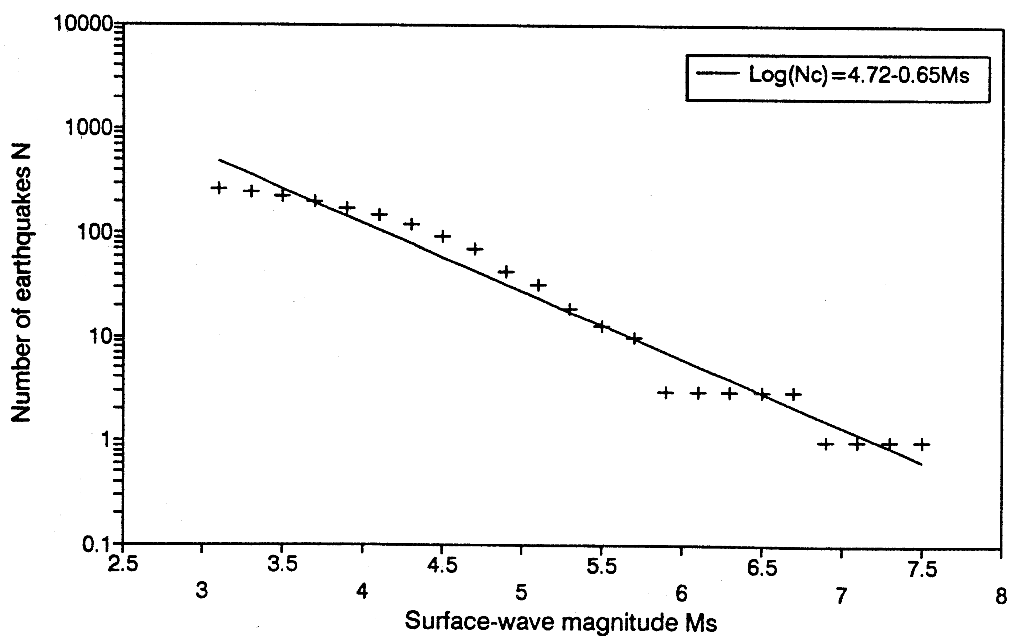


Fig. 7b. Frequency-magnitude relation in Algeria (1900-1990) using complete file with $M_S \geq 3.0$.

b) Complete file:

$$\text{Log}(N_c) = 4.72 - 0.65\,(M_S) \quad (r = 0.97) \qquad (5.7)$$

Figures 7a,b show a plot of the cumulative frequency-magnitude relation for Algeria (1900-1990) using incomplete and complete files of shallow earthquakes, where N_c represents the cumulative frequency and r is the correlation coefficient.

Comparing the recurrence formulae derived from the cumulative frequency in the three regions, for incomplete and complete files, it is found that the fitting equations are quite similar. The differences between the b-values in the Maghreb region, the Atlas mountains and Algeria are found to be respectively 1.2, 1.3 and 3.0 percent. These differences of the b-values are found to be too small to affect the evaluation of seismic hazard and risk in each study area. On the other hand, the comparison of b-values, derived from the single and cumulative frequencies and for incomplete and complete files, for each zone vary from an average of 30 percent in the Maghreb, to 50 in the Atlas and 86 percent in Algeria. This is obviously due to the effect of incompleteness of the data set in the region. The above results show that the effect of incompleteness can, to a certain extent, be reduced by increasing the size of the area from which the sample is drawn, which means increasing the size of the data sample.

From figs. 5a,b to 7a,b, it may concluded that the seismicity in each of the three study zones is diffuse and consists of a large number of shallow earthquakes with relatively moderate to small magnitudes.

6. Seismic strain in the Atlas

This section presents the estimation of the total seismic strain throughout the Atlas mountains during the twentieth century. This analysis is carried out for two main reasons. The first is to show graphically the overall twentieth century seismic activity of the Atlas as a whole. The second is to evaluate the overall seismic strain during this century in order to compare it with other recent estimations from plate motions of McKenzie (1972) and Minster and Jordan (1978) and from paleoseismology of Meghraoui (1988).

The scalar seismic moment for each event can be calculated from the empirical relationship between the surface-wave magnitude M_S and M_0 (Ekström and Dziewonski, 1988):

$$\text{Log}(M_0) = 19.24 + M_S \qquad (M_S \le 5.3)$$
$$\text{Log}(M_0) = 30.20 - \sqrt{(92.45 - 11.40\,M_S)} \qquad (5.3 \le M_S \le 6.8)$$
$$\text{Log}(M_0) = 16.14 + 1.5\,M_S \qquad (M_S \ge 6.8) \qquad (6.1)$$

and the cumulative seismic moment (M_0) in the zone can also be estimated from Aki (1966):

$$M_0 = \mu L d r \qquad (6.2)$$

where μ is the shear modulus, L the length of the zone, d the slip depth and r is the relative displacement.

The average slip rate in the Atlas is obtained by combining eqs. (6.1) and (6.2). Using Ekström's relations (6.1), the cumulative seismic moment for shallow earthquakes in the Atlas (1900-1990) with magnitudes $M_S \geqslant 4.5$ is found to be equal to 3.1×10^{27} dyn-cm. The results are presented in fig. 8 which displays the overall seismic moment (ΣM_0) of the Atlas versus time for shallow events with magnitudes $M_S \geqslant 4.5$. In order to estimate the relative slip rate from eq. (6.2), knowing (ΣM_0), it is necessary to define the dimensions of the zone under consideration. The Atlas zone has a length (E-W) of 2300 km, a width (N-S) of 400 km, and a thickness of 15 km. The thickness of the layer, taken here as 15 km, within which most seismic energy is released, is based on the depth of focus of most earthquakes in the Atlas (see section 4), but this could be inaccurate by a few kilometres. For the Atlas, assuming an av-

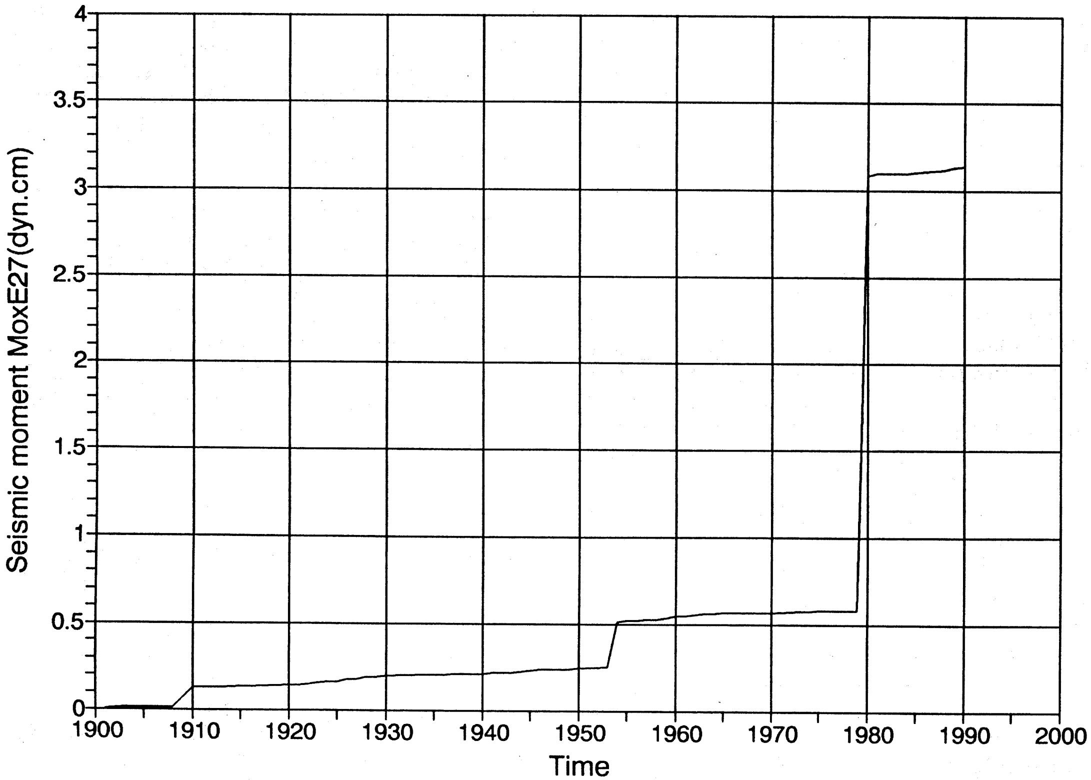


Fig. 8. Cumulative seismic moment for shallow events with magnitudes $M_S \geq 4.5$ in the Atlas zone during the period 1900-1990.

erage dip angle thrusting of $\theta = 50°$ in a 15 km thick layer (h) with $\mu = 3.3 \times 10^{11}$ dyn./cm^2, the average slip rate is given by:

$$r = (\Sigma M_0 \sin\theta)/(\mu \mathrm{TLh}) = 2.31 \text{ mm/year} \quad (6.3)$$

which corresponds to a horizontal shortening slip rate of 1.48 mm/year and an uplift slip rate of 1.76 mm/year in the whole Atlas.

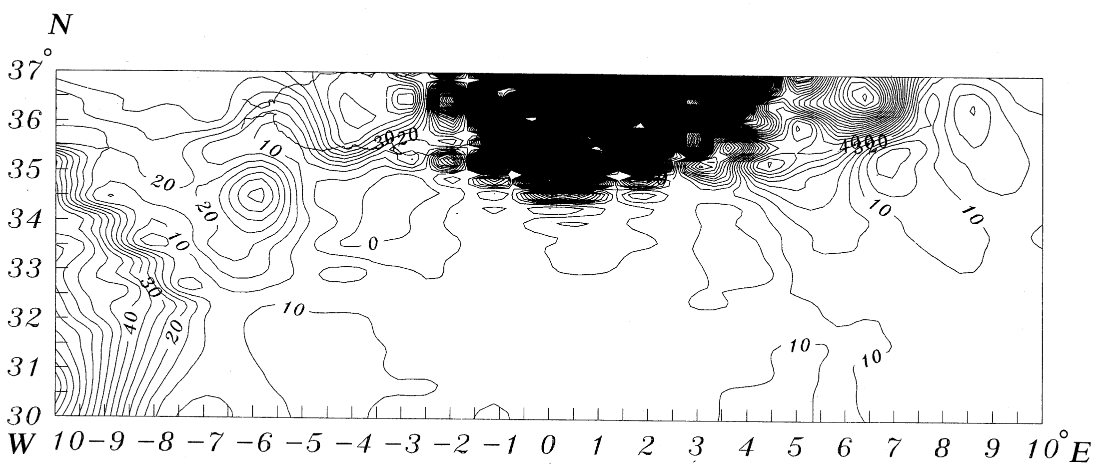
From fig. 8 it can easily be noticed that the 91-year time of observation is too short to be representative of longer periods of the seismic activity in the Atlas. It illustrates the seismicity in the Atlas for the specific period 1900-1990, and no conclusions can be drawn for longer periods. Smaller events do not contribute very much to the total seismic moment, the rate of which is not significantly affected and thus are not taken into account; the contribution of uncertainties in M_0 are far more important. The intermediate and deep earthquakes constitute another uncertainty in the seismic strain evaluation. Ambraseys and Jackson (1990) have shown that these earthquakes do not add to the deformation of the upper seismogenic layer, and thus should not be taken into account in the strain computation. This can be confirmed by estimating the strain for both shallow and intermediate earthquakes within the Atlas zone. Because the number and size of these events is small, it is found that their

Table I. Slip rates (mm/year) calculated from shallow earthquakes with $M_S \geqslant 4.5$, with average standard error of ($\pm$ 0.25), during 1900-1990.

Direction	Minimum	Probable	Maximum
Shortening	0.63	1.48	3.42
Uplift	0.75	1.76	4.08

inclusion or exclusion does not make any important change. The main uncertainty in the seismic strain estimates, as stated previously, comes rather from the uncertainty in M_0, with the uncertainty due to relatively small strike and dip (Jackson and McKenzie, 1988). Therefore, in this work, the uncertainty in seismic strain is determined from the uncertainty of surface-wave magnitudes M_S. This shows the possibility of a systematic biased seismic strain, thus standard deviations are not computed but simply given minimum and maximum probable estimates, taking into account that all surface-wave magnitudes may be under- or over-estimated. The average standard error in surface-wave magnitudes M_S calculated in this work is found to be equal to $\pm$ 0.25. A range of minimum to maximum seismic strain values is then obtained. The minimum and maximum estimates of the strain differ respectively by factors of 2 and 2.5 from that obtained from the calculated average M_S values. The results of slip rates (mm/year) calculated from shallow earthquakes of $M_S \geqslant 4.5$ and taking an average standard error of ($\pm$ 0.25) in the period 1900-1990 are presented in table I.

In comparing these results with those evaluated recently by different authors using different methods, it is found that the average uplift of 1.76 mm/year is very similar to that determined at 1.52 mm/year from trench data by Meghraoui (1988). On the other hand the shortening rate in the Atlas of 1.48 mm/year represents about 30 percent of the value calculated from plate tectonic motions by McKenzie (1972) and Minster and Jordan (1978). There are two possible reasons for the difference between the two values. The first one concerns the slip rate of 1.48 mm/year, which could be seriously underestimated since the moment-magnitude relation is not known for the region. The second one is that it is supposed that, during each event, the slip takes place across the whole Atlas. It remains possible that the slip occurs only during major earthquakes in certain sections of



Map. 1. Distribution of seismic moments ($\times 10^{23}$ dyn./cm) in the Atlas block (30°-37°N, 10°W-10°E).

the zone, whereas elsewhere its occurs without their help. If this difference is real, it means that the major parts of the compressive deformations in the Atlas are continuous and produced aseismically, and that the short-term seismicity does not reflect the tectonic activity in the Atlas. This confirms the previous conclusion that, in the Atlas, the moment rate averaged over a 91-year period is not representative of the seismic activity for longer periods.

In order to show graphically the distribution of the seismic strain in the Atlas block, the zone has been divided into squares of 0.5 degree of cross sections within which the corresponding cumulative seismic moments are calculated. Each cumulative moment is then reported at the centre of the respective square; the results are presented in map 1.

7. Conclusions

As a result of this analysis, it can be confirmed that seismic activity in the Atlas is scattered and involves a large number of relatively small earthquakes. These events, which are mainly shallow, occur with no evident association with tectonic features, no clear pattern of occurrence, and with little indication of obvious faulting except during the Orléansville 1954 and El-Asnam 1980 earthquakes.