

## Seismic Empirical Relations for the Tellian Atlas, North Africa, and their Usefulness for Seismic Risk Assessment

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**Abstract**—Seismic events that occurred during the past half century in the Tellian Atlas, North Africa, are used to establish fundamental seismic empirical relations, tying earthquake magnitude to source parameters (seismic moment, fault plane area, maximal displacement along the fault, and fault plane length). Those empirical relations applied to the overall seismicity from 1716 to present are used to transform the magnitude (or intensity) versus time distribution into (1) cumulative seismic moment versus time, and (2) cumulative displacements versus time. Both of those parameters as well as the computed seismic moment rate, the strain rate along the Tellian Atlas strike, and various other geological observations are consistent with the existence, in the Tellian Atlas, of three distinct active tectonic blocks. These blocks are seismically decoupled from each other, thus allowing consideration of the seismicity as occurring in three different distinct seismotectonic blocks. The cumulative displacement versus time from 1900 to present for each of these tectonic blocks presents a remarkable pattern of recurrence time intervals and precursors associated with major earthquakes. Indeed, most major earthquakes that occurred in these three blocks might have been predicted in time. The Tellian Atlas historical seismicity from the year 881 to the present more substantially confirms these observations, in particular for the western block of the Tellian Atlas. Theoretical determination of recurrence time intervals for the Tellian Atlas large earthquakes using Molnar and Kostrov formalisms is also consistent with these observations. Substantial observations support the fact that the western and central Tellian Atlas are currently at very high seismic risk, in particular the central part. Indeed, most of the accumulated seismic energy in the central Tellian Atlas crust has yet to be released, despite the occurrence of the recent destructive May 2003 Boumerdes earthquake ( $M_w = 6.8$ ). The accumulated seismic energy is equivalent to a magnitude 7.6 earthquake. In situ stress and

geodetic measurements, as well as other geophysical field data measurements, are now required to practically check the validity of those observations.

**Key words:** Atlas fault belt system, Seismic moment rate, Time predictable models, Strain rate, Fault rupture characteristics, Focal mechanisms, Molnar, and Kostrov formalisms.

### 1. Introduction

The current northern Africa deformation is reflected by the spectacular currently active topography of the Atlas fault system (McKENZIE, 1972; MATTAUER *et al.*, 1977; BARAZANGI, 1983; DEWEY *et al.*, 1989; UDIAS and BUFORN, 1991; GOMEZ *et al.*, 2000) (Fig. 1).

The convergence of the African and Eurasian plates at a rate of about 1.1 cm/year (BUFORD *et al.*, 1995; MINSTER and JORDAN, 1978) is responsible for the buildup of the large-scale Atlas fault belt system and regularly triggers deadly earthquakes, such as the 1954 Orleansville (Algeria) (Mag 6.7), 1960 Agadir (Morocco) (Mag 5.7), 1980 El-Asnam (i.e., Chleff, Orléanville) (Algeria) (Mag 7.3), and May 2003 Boumerdes (Algeria) (Mag 6.8) events, which claimed respectively over 1,500, 12,000, 3,000 and 2,800 lives.

Instrumental and historical seismicity, surface rupture characteristics and focal mechanisms of recent major earthquakes are used to provide useful parameters that offer insight about the overall Tellian Atlas seismicity, in order to obtain better seismic hazard assessment in the region. The objective of this study is threefold:

- to lay down very useful basic quantitative empirical relations that satisfactorily describe the Tellian

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Atlas physical deformation and seismicity and endeavor to give insight about the overall Maghreb (i.e., North African) seismicity;

- to theoretically, as well as observationally, evaluate for different regions of the Maghreb the recurrence time interval of catastrophic earthquakes, such as the magnitude 7.3 1980 event that destroyed most of El-Asnam city (KING and VITA-FINZI, 1980; OUYED and MEGHRAOUI, 1981; DESCHAMPS *et al.*, 1982; PHILIP and MEGHRAOUI, 1983; BEGHOUL, 1984, MEGHRAOUI, 1988), or the Algiers event that killed over 20,000 people in 1716 (AMBRASEYS, 1983). Those theoretical evaluations of major events time recurrence intervals will be tested against our current knowledge of the historical seismicity of the Maghreb region.
- Finally, we show that the collision of the African plate with the Eurasian plate is accommodated differently from West to East. A simple differentiation of the northern Tellian Atlas in three different seismotectonic regions allows establishment of the fact that stress accumulation and release in the three regions are far from being random but work with an astonishing regularity, in which most major earthquakes that occurred in the Tellian Atlas might have been predicted in time. To achieve this goal, four main seismic parameters are constructed for each region: (1) the cumulative seismic moment versus time, (2) the cumulative displacement versus time, (3) the derivative of the cumulative displacement versus time, and (4) a velocity term based on the second parameter.

Those computed seismic parameters shed light on several aspects of the deformation patterns in the Tellian Atlas and lead to some quantitative laws that satisfactorily describe the overall seismicity temporal distribution in each region.

There are tremendous implications regarding seismic risk assessment. This study determines what the patterns of those parameters are when a region becomes seismically very hazardous. Substantial observations are presented which show that the western and the central Tellian Atlas blocks are both presently at very high seismic risk, in particular the central part. The seismic energy stored in the crust in the central Tellian Atlas that has not been released is

equivalent to a 7.6 magnitude earthquake, despite the recent occurrence of the magnitude 6.8 May 2003 destructive Boumerdes earthquake.

## 2. The Tellian Atlas as three Distinct Tectonic Blocks

Based on the following observations, the Tellian Atlas may be divided into three different seismotectonic blocks, namely the eastern, central and western blocks (Fig. 1).

- (a) The dramatic change in the outcrops from west to east. The eastern Tellian Atlas is characterized by a large spreading of the Permian Saharan Atlas rocks (Fig. 1), while the central and western Tellian Atlas are made of Miocene overthrust allochthonous Alpine nappes (Fig. 1).
- (b) The difference in nature and style of the Quaternary faulting from west to east (MEGHRAOUI, 1988) (see Fig. 1 and Table 1). The western and the central fault system works in thrust faulting mechanism whereas, the eastern part accommodates the deformation with mostly a strike slip faulting mechanism. This lateral variation of the deformation from west to east is largely controlled by (1) the narrowing of the rigid undeformed block of the High Plains (Fig. 1), and (2) the state of “blocage” in the western part (0.5 cm/year), while the eastern part converges at about 2.8 cm/year (McKENZIE, 1972; MINSTER and JORDAN, 1978).

The western fault system has a NE–SW direction with considerably shorter faults than in the central part. The central fault system is distributed *en échelon*, mainly in an east–west direction, along a much larger width (MEGHRAOUI, 1988). It seems that the fault directions are controlled by the width of the rigid aseismic undeformed High Plains varying from west to east (Fig. 1). Moreover, various geological field mappings of mega folds axes (TAPPONNIER, 1977) and of active and inactive faults lineaments (MEGHRAOUI, 1988), as well as TM-Landsat images analysis (BEAUCHAMP, 1998) (Fig. 1), demonstrate the existence of this coherent and continuous NE-oriented lineament and fold system extending from Meknes to western Algiers. The related seismicity is located in the corridor lying in-between the mega folds.

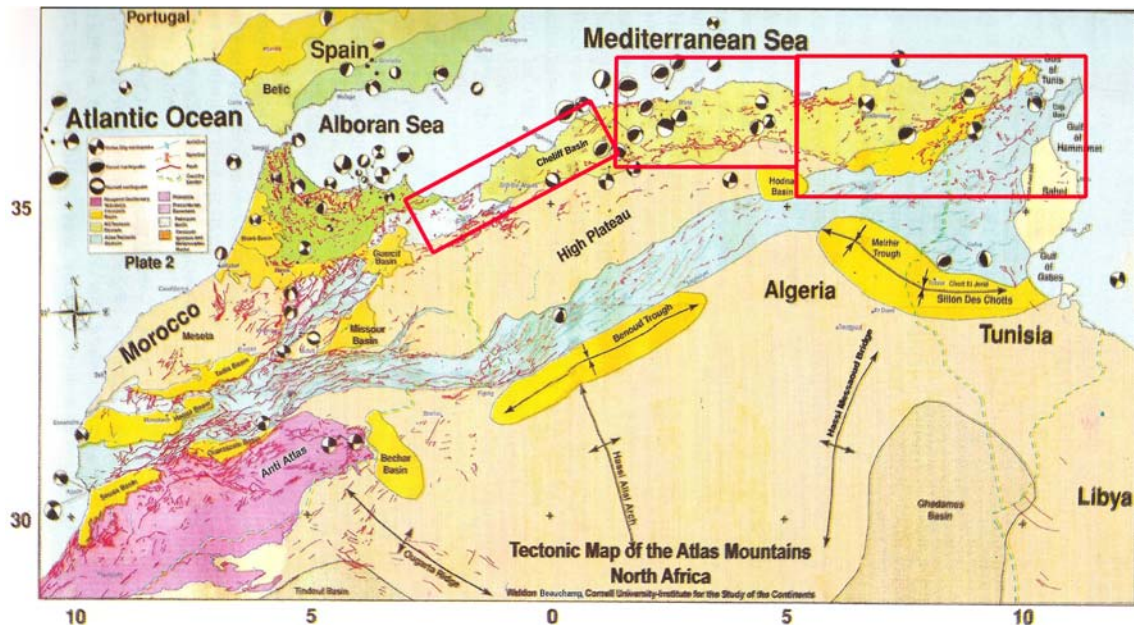


Figure 1

Seismotectonic map of the Maghreb region, North Africa (BEAUCHAMP, 1998) with the delineation of the different physio-geographic tectonic domains and their corresponding mode of fracturation represented by the focal mechanisms of recent earthquakes. Note the bending and dramatic width decrease of the High Plateau in the Algiers region. The rectangles represent the three studied seismotectonic blocks of the Tellian Atlas with the greatest seismic risk

- (c) From FABRE (1978) geological map (Fig. 2) it appears that the *en echelon* fault system reported by MEGHRAOUI (1988) in Central Algeria is bounded on the west and the east by distinct major thrust faults separating the three blocks. We demonstrate that one of these major western fault thrusts is currently active. Preliminary results of an ongoing work point out that most of the other major thrust faults also are currently active.
- (d) The central Tellian seismicity shows a major change in azimuth with a seismicity kink changing from the overall NE straight pattern of the western lineament (Meknes—Oran - El-Asnam—Algiers) to a SE direction extending from Algiers—Blida to M'Sila (Fig. 3).
- (e) In the eastern Tellian Atlas no earthquake with magnitude larger than 6.5 has occurred, while in the central and western Tellien Atlas magnitudes as large as 7.3 have been reported.

This division of the Tellian Atlas into three blocks is mainly based on geomorphologic, seismotectonic

global observations. The question arises then, do these blocks have different mechanical and seismic properties, and what are the consequences on risk mitigation ?

In this study the western Tellian Atlas excludes the Rif region (see Fig. 1). Indeed, the Rif seismicity is the reflection of complex thermo-mechanical processes (SEBER *et al.*, 1996; CALVERT *et al.*, 2000), and therefore does not exclusively represent the absorbed mechanical deformation related to the African-Eur-Asia plate convergence.

### 3. Data

#### 3.1. Seismic Data

Data used in this study includes the Maghreb instrumental seismicity from the following catalogues:

- the ISC Bulletin from 1964 to 2007;






Table 1

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Lon min = -2.82; Lon max = 2.0. Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Lon min = 2.00; Lon max = 5.0. Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Lon min = 5.00; Lon max = 11.9

Time and location	Mag = Max( $m_b, M_s$ )	$M_0$ [dynes-cm]	Faults planes	Focal mechanism
October 10th 1980 Lat = 37.95, Long = 11.49	7.3	$5.07 \times 10^{26}$	Strike = 235, dip = 45, slip = 67 Strike = 87, dip = 50, slip = 111	
October 10th 1980 Lat = 36.25, Long = 1.36	6.2	$2.24 \times 10^{25}$	Strike = 247, dip = 30, slip = 105 Strike = 50, dip = 61, slip = 81	
October 13th 1980 Lat = 36.53, Long = 2.07	5.2	$2.27 \times 10^{24}$	Strike = 63, dip = 42, slip = 69, Strike = 271, dip = 51, slip = 108	
November 8th 1980 Lat = 36.02, Long = 1.32	5.3	$7.59 \times 10^{23}$	Strike = 270, dip = 45, slip = 126 Strike = 44, dip = 55, slip = 59	
December 5th 1980 Lat = 35.87, Long = 1.68	5	$1.13 \times 10^{24}$	Strike = 112, dip = 61, slip = -179 Strike = 21, dip = 89, slip = -29	
December 7th 1980 Lat = 36.02, Long = 0.94	5.6	$2.91 \times 10^{24}$	Strike = 277, dip = 40, slip = 140 Strike = 39, dip = 66, slip = 57	
January 15th 1981 Lat = 36.38, Long = 1.38	5	$3.67 \times 10^{23}$	Strike = 181, dip = 53, slip = 29 Strike = 72, dip = 67, slip = 139	
February 1st 1981 Lat = 36.27, Long = 1.90	5.7	$2.69 \times 10^{24}$	Strike = 210, dip = 43, slip = 64 Strike = 64, dip = 52, slip = 112	
February 14th 1981 Lat = 36.08, Long = 1.76	5	$7.39 \times 10^{23}$	Strike = 26, dip = 67, slip = -18 Strike = 124, dip = 73, slip = -156	
November 15th 1982 Lat = 35.73, Long = 1.15	5	$8.34 \times 10^{23}$	Strike = 274, dip = 70 slip = -169 Strike = 180, dip = 80, slip = -20	
October 27th 1985 Lat = 36.46, Long = 6.87	5.9	$6.21 \times 10^{24}$	Strike = 213, dip = 71, slip = 20 Strike = 117, dip = 71, slip = 160	
October 31st 1988 Lat = 36.44, Long = 2.63	5.6	$3.15 \times 10^{24}$	Strike = 103, dip = 55, slip = 167 Strike = 201, dip = 79, slip = 36	
January 3rd 1989 Lat = 35.79, Long = 11.80	5	$5.44 \times 10^{23}$	Strike = 247, dip = 90, slip = 180  Strike = 337, dip = 90, slip = 0	
October 29th 1989 Lat = 36.84, Long = 2.92	5.9	$9.65 \times 10^{24}$	Strike = 91, dip = 48, slip = 119 Strike = 231, dip = 50, slip = 62	
February 9th 1990 Lat = 36.26, Long = 2.83	5	$8.2 \times 10^{23}$	Strike = 49, dip = 18, slip = 95  Strike = 225, dip = 72, slip = 88	
June 12th 1992 Lat = 34.21, Long = 8.44	5.3	$6.97 \times 10^{23}$	Strike = 82, dip = 36, slip = 114 Strike = 233, dip = 57, slip = 73	
August 18th 1994 Lat = 35.60, Long = 0.36	5.9	$6.86 \times 10^{24}$	Strike = 40, dip = 23, slip = 70 Strike = 241, dip = 69, slip = 98	
September 22nd 1995 Lat = 35.54, Long = 7.87	5	$1.29 \times 10^{24}$	Strike = 173, dip = 41, slip = 8 Strike = 270, dip = 84, slip = -130	
September 4th 1996 Lat = 37.03, Long = 3.03	5.3	$1.91 \times 10^{24}$	Strike = 11, dip = 76, slip = -4 Strike = 102, dip = 86, slip = -166	
December 22nd 1999 Lat = 35.34, Long = -1.45	5.5	$2.95 \times 10^{24}$	Strike = 29 dip = 45 slip = 67 Strike = 240, dip = 49, slip = 111	
August 18th 2000 Lat = 36.12, Long = 5.00	5.1	$7.34 \times 10^{23}$	Strike = 99, dip = 71, slip = -171  Strike = 6, dip = 81, slip = -19	
November 10th 2000 Lat = 36.45, Long = 4.96	5.8	$4.29 \times 10^{24}$	Strike = 64, dip = 38, slip = 97 Strike = 235, dip = 52, slip = 85	
June 24th 2002 Lat = 36.03, Long = 10.29	4.9	$7.33 \times 10^{23}$	Strike = 28, dip = 48, slip = 128 Strike = 158, dip = 54, slip = 56	
May 21st 2003 Lat = 36.93, Long = 3.58	6.9	$2.01 \times 10^{26}$	Strike = 57, dip = 44, slip = 71  Strike = 262, dip = 49, slip = 107	
May 27th 2003 Lat = 36.94, Long = 3.79	5.5	$3.94 \times 10^{24}$	Strike = 70, dip = 31, slip = 92 Strike = 248, dip = 59, slip = 89	



**Table 1** continued

Time and location	Mag = Max( $m_b$ , $M_s$ )	$M_0$ [dynes-cm]	Faults planes	Focal mechanism
May 29th 2003 Lat = 36.84, Long = 3.55	4.9	$6.07 \times 10^{23}$	Strike = 14, dip = 59, slip = 5	
March 20th 2006 Lat = 36.62, Long = 5.32	5	$7.21 \times 10^{23}$	Strike = 282, dip = 86, slip = 149 Strike = 92, dip = 64, slip = -174	
April 2nd 2006 Lat = 35.03, long = 3.66	4.7	$5.04 \times 10^{23}$	Strike = 360, dip = 84, slip = -26 Strike = 66, dip = 79, slip = -178	
August 7th 2006 Lat = 35.00, Long = 3.70	4.7	$2.54 \times 10^{23}$	Strike = 335, dip = 88, slip = -11 Strike = 58, dip = 71, slip = 171	
July 9th 2007 Lat = 34.10, Long = 6.89	4.7	$2.22 \times 10^{23}$	Strike = 151, dip = 82, slip = 19 Strike = 64, dip = 62, slip = 165 Strike = 161, dip = 76, slip = 29	

- the Harvard moment tensor solutions of earthquakes, with magnitudes larger than 5.0, from January 1976 to July 2007 (Table 1);
- the Algerian seismicity from 1951 to 1970 assembled (BENHALLOU *et al.*, 1971);
- the Maghreb seismicity, with more emphasis on the Algerian seismicity from 1900 to 1995 (BENOUAR, 1996).

Data also includes historical and/or instrumental seismicity from the following catalogues:

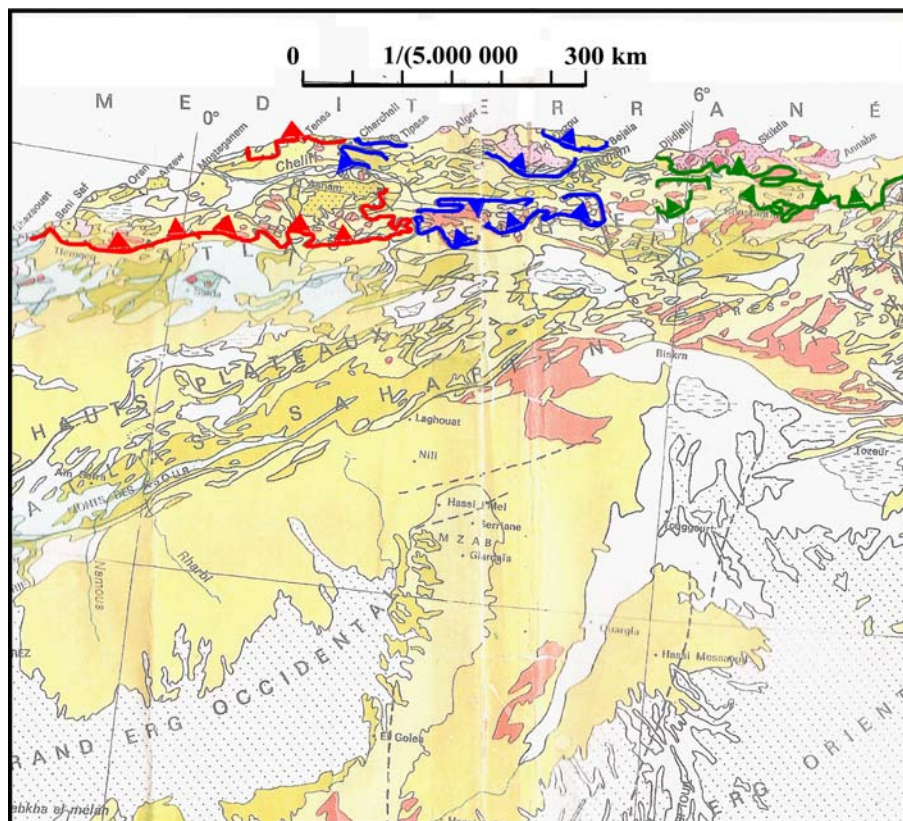


Figure 2

Geological map of the central part of Algeria, North Africa (adapted from FABRE, 1978). The major Tellian Atlas thrusts fronts are represented by thick lines with filled triangles

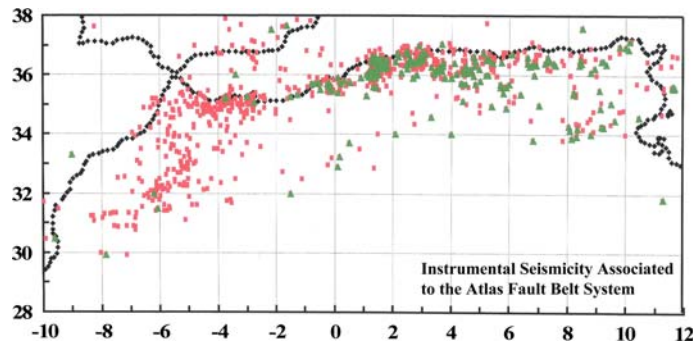


Figure 3

Instrumental seismicity map of the Maghreb region, North Africa from 1900 to present. *Points* are earthquakes with a magnitude less than 4.5 and *triangles* are events with a magnitude greater or equal to 4.5. The seismicity outlines the seismotectonic features of Fig. 1. Note, in particular, the seismic gap outlining the rigid undeformed High Plains. Most earthquakes occurring in the western part are small size events, contrasting with Northern Algeria and Tunisia where most magnitudes larger than 4.5 events occur

- the catalogue of the Historical seismicity of Spain, the Maghreb and the Middle East from the VII to the XIII century (POIRIER and TAHER, 1980);
- the Algerian seismicity from 1365 to 1992 (MOKRANE *et al.*, 1994);
- the largest Algerian earthquakes from 1365 to 1989 (AYADI, 1996);
- the seismicity of the central part of Algeria from 1365 to 1989 (SEBAÏ and OUAHMED, 1997);
- the Algerian seismicity from 1716 to 2000 (BOUGHACHA *et al.*, 2003).

Historical seismicity is used to check whether the patterns of major earthquakes time recurrence intervals, as well as their precursors, evidenced from the instrumental seismicity are also observed within a larger time scale. When available, earthquake spatial and temporal distributions, damage extension and distribution, as well as individual reaction are used rather than the speculative intensities reported in most historical catalogues.

Given the uncertainties associated with historical earthquakes, considerable amounts of time have been spent checking the location and size of earthquakes, specifically those exceeding magnitude 6.0.

Locations and magnitudes of earthquakes used in this study are a synthesis of all these data sets (Table 2).

### 3.2. Field and Seismic Parameters

The second set of data used in this study deals with source parameters and surface fault rupture characteristics of recent relatively large Maghreb earthquakes (Tables 1, 2). Those parameters have mainly been determined through field studies and acquired by mapping the surface fault ruptures (PHILIP and MEGHRAOUI, 1983) or by seismicity monitoring with post-event arrays. These parameters are used to establish empirical relations that give the correspondence between the magnitude  $m_b$  of an earthquake and its corresponding source parameters: fault plane area  $A$ , maximal displacement along the fault  $D_{max}$ , fault plane length  $L$ , and seismic moment  $M_0$ , in order to evaluate past event source parameters, for which the only available data are the magnitude  $m_b$ .

### 3.3. Data Validity Test

Aftershocks representing the geometry of the fault plane ( $A$  and  $L$ ) have to be reasonably well located. In order to check the validity and goodness of both the surface rupture mapping and aftershock locations, two fundamental properties are used:

1. the seismic moment of the main shock from the aftershock distribution and/or from surface fault

Table 2

*New preliminary compilation of events of  $Mag \geq 4.7$  located in the Atlas System and reported by several published catalogues*

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1365	1	2	0	0	0.0000	0.0000	Mag $\geq$ 6.0	-	(Ayadi)
							-	7.7	(Beghoul & Dadou)
							-	-	(Sebaï & Ouahmed)
							-	-	(Mokrane et al.)
1673	3	10	21	0	36.7000	3.1000	Mag $\geq$ 6.0	-	(Ayadi)
							VIII	5.7	(Mokrane et al.)
							VIII	-	(Sebaï & Ouahmed)
							-	6.7	(Beghoul & Dadou)
1716	2	3	2	0	36.7000	3.1000	-	6.2	(Boughacha et al.)
							Mag $\geq$ 6.0	7.5	(Ayadi)
							IX	6.5	(Mokrane et al.)
							IX	-	(Sebaï & Ouahmed)
							Mag $\geq$ 6.0	7.5	(Beghoul & Dadou)
1716	5	0	0	0	36.7000	3.1000	-	5.5	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
							VIII	-	(Sebaï & Ouahmed)
1717	0	0	0	0	36.7000	3.1000	-	5.5	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
							VIII	-	(Sebaï & Ouahmed)
1717	8	5	23	30	36.7000	3.1000	-	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
							VII	-	(Sebaï & Ouahmed)
1722	11	29	0	0	36.7000	3.1000	-	4.7	(Boughacha et al.)
							Mag $\geq$ 6.0	-	(Ayadi)
							VII	5.2	(Mokrane et al.)
							VII	-	(Sebaï & Ouahmed)
							Mag $\geq$ 6.0	7.5	(Beghoul & Dadou)
1780	6	8	4	0	36.42	3.06	-	-	(Boughacha et al.)
1780	6	30	13	0	36.42	3.06	-	-	(Boughacha et al.)
1790	10	9	1	15	35.7000	-0.6500	-	7.2	(Boughacha et al.)
							Mag $\geq$ 6.0	6.5-7.5	(Ayadi)
							X	7.5	(Mokrane et al.)
							Mag $\geq$ 6.0	7.3	(Beghoul & Dadou)
1804	9	26	21	15	36.5700	-2.8200	-	6.4	(Boughacha et al.)
1807	11	18	0	0	36.7000	3.0900	-	4.7	(Boughacha et al.)
							-	-	(Mokrane et al.)
							VII	-	(Sebaï & Ouahmed)
1819	3	0	0	0	35.4000	0.1000	-	5.5	(Boughacha et al.)
							Mag $\geq$ 6.0	6.5	(Ayadi)
							X	7.5	(Mokrane et al.)
							Mag $\geq$ 6.0	6.5	(Beghoul & Dadou)
1825	3	2	7	0	36.4500	2.8167	-	6.4	(Boughacha et al.)
							Mag $\geq$ 6.0	7.5	(Ayadi)
							X-XI	7.5-8.4	(Mokrane et al.)
							X-XI	-	(Sebaï & Ouahmed)
							Mag $\geq$ 6.0	7.5	(Beghoul & Dadou)
1842	12	4	3	0	36.7000	3.1000	-	4.7	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
							VII	-	(Sebaï & Ouahmed)
1847	6	18	5	40	36.7000	2.9000	VII	5.2	(Mokrane et al.)
1850	2	9	0	0	36.3000	4.8000	-	5.5	(Boughacha et al.)
							VIII-IX	5.7-6.5	(Mokrane et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1851	11	22	9	30	35.4000	0.1000	–	4.7	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1854	5	15	15	0	36.4667	2.8333	–	4.7	(Boughacha et al.)
							–	–	(Mokrane et al.)
							VII	–	(Sebäi & Ouahmed)
1856	8	21	22	0	37.1000	5.7000	–	5.5	(Boughacha et al.)
							Mag $\geq$ 6.0	7.5	(Ayadi)
							VIII–X	7.5	(Mokrane et al.)
							Mag $\geq$ 6.0	6.5	(Beghoul & Dadou)
1858	3	9	4	30	36.3667	2.1667	–	6.7	(Boughacha et al.)
							Mag $\geq$ 6.0	6.5	(Ayadi)
							VI–VII	4.6–5.2	(Mokrane et al.)
							VII	–	(Sebäi & Ouahmed)
							Mag $\geq$ 6.0	6.6	(Beghoul & Dadou)
1860	9	27	0	0	36.3000	4.5000	–	4.7	(Boughacha et al.)
							–	–	(Mokrane et al.)
1861	3	29	5	15	36.5000	2.9000	–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
							VII	–	(Sebäi & Ouahmed)
1861	7	26	17	20	35.7000	-0.6000	–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1865	2	25	2	14	36.7500	5.0800	–	4.7	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1867	1	2	7	13	36.4300	2.7200	–	5.5	(Boughacha et al.)
							Mag $\geq$ 6.0	7.5	(Ayadi)
							X–XI	7.5–8.4	(Mokrane et al.)
							X–XI	–	(Sebäi & Ouahmed)
							Mag $\geq$ 6.0	6.6	(Beghoul & Dadou)
1867	2	3	8	20	38.0000	-0.7000	–	4.7	(Boughacha et al.)
1869	11	16	0	0	34.9000	5.9000	–	6.4	(Boughacha et al.)
							Mag $\geq$ 6.0	6.5	(Ayadi)
							IX	6.5	(Mokrane et al.)
							Mag $\geq$ 6.0	6.5	(Beghoul & Dadou)
1872	7	29	8	15	35.9200	0.1000	–	4.7	(Boughacha et al.)
1874	3	28	11	12	36.6000	2.2000	–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
							VII	–	(Sebäi & Ouahmed)
1876	3	23	6	34	36.5000	2.6000	–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
							VII	–	(Sebäi & Ouahmed)
1885	1	17	0	0	35.5000	5.7000	–	5.5	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1885	12	3	20	0	36.1000	4.6000	–	5.5	(Boughacha et al.)
							–	–	(Mokrane et al.)
1886	7	1	9	45	36.5000	5.3000	–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1886	9	22	15	0	36.2000	3.6000	–	4.7	(Boughacha et al.)
1887	1	8	20	0	36.1000	4.6000	–	4.7	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1887	11	29	13	25	35.8000	0.3300	–	5.5	(Boughacha et al.)
							Mag $\geq$ 6.0	6.5–7.5	(Ayadi)
							IX–X	6.5–7.5	(Mokrane et al.)
							Mag $\geq$ 6.0	7.0	(Beghoul & Dadou)



**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1888	1	6	23	40	36.5000	2.6000	–	5.5	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1889	5	21	4	15	35.7000	-0.8000	–	4.7	(Boughacha et al.)
							VII–VIII	5.2–5.7	(Mokrane et al.)
1890	7	30	0	0	35.7000	0.5000	VI–VII	4.6–5.2	(Mokrane et al.)
1891	1	15	4	0	36.5000	1.8333	–	6.4	(Boughacha et al.)
							Mag ≥ 6.0	7.5	(Ayadi)
							X	7.5	(Mokrane et al.)
							X	–	(Sebaï & Ouahmed)
							Mag ≥ 6.0	7.2	(Beghoul & Dadou)
1900	4	25	0	0	35.7000	-0.6000	VI	–	(Benouar)
							VI–VII	4.6–5.2	(Mokrane et al.)
							VI–VII	4.6–5.2	(Mokrane et al.)
1901	1	13	0	0	36.6200	4.6800	IX	–	(Benouar)
							IX	6.5	(Mokrane et al.)
1903	9	23	1	55	36.3133	2.8300	VII	5.6	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Sebaï & Ouahmed)
1903	11	24	0	0	37.6000	-2.0000	VII	4.9	(Benouar)
1903	11	25	0	0	37.6000	-2.0000	VII	4.9	(Benouar)
1907	2	21	15	7	35.7000	1.3400	VI	4.4	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1907	4	16	17	30	37.8000	-1.5000	VII	4.7	(Benouar)
1907	9	1	0	0	36.4000	6.6000	–	5.5	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1908	3	10	23	21	36.5000	2.9000	VII	4.7	(Benouar)
1908	3	11	0	6	36.4250	2.8000	VIII	5.0	(Benouar)
							–	4.7	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
							VIII	–	(Sebaï & Ouahmed)
1908	6	9	19	51	36.5000	2.9000	VII	4.5	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Sebaï & Ouahmed)
1908	6	17	0	24	36.5000	7.5000	VIII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII–VIII	5.2–5.7	(Mokrane et al.)
1908	8	4	2	11	36.4033	6.6033	VIII	5.1–5.2	(Benouar)
							–	5.1	(Boughacha et al.)
							VIII	5.1–5.7	(Mokrane et al.)
1909	7	1	14	12	38.0000	-0.6850	VII	3.7	(Benouar)
							–	4.7	(Boughacha et al.)
1910	2	2	1	0	35.7000	-0.2000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1910	6	24	13	28	36.0500	3.4200	–	6.6	(Boughacha et al.)
							Mag ≥ 6.0	6.4–6.6	(Ayadi)
							X	6.4–7.5	(Mokrane et al.)
1910	8	20	1	20	36.1000	3.4000	VII	4.7	(Benouar)
1911	1	7	1	33	36.1000	3.4000	VI	5.1	(Benouar)
1911	3	21	14	15	38.0000	-1.2000	VIII	5.5	(Benouar)
1912	4	22	3	0	37.0000	-2.8000	VII	4.9	(Benouar)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1912	7	24	18	6	35.8000	-0.3500	-	4.7	(Boughacha et al.)
							VII	4.9	(Mokrane et al.)
1912	8	6	18	44	36.9800	4.6200	VI	5.0-5.3	(Benouar)
							-	5.3	(Boughacha et al.)
							VI	4.5-5.3	(Mokrane et al.)
1912	8	25	21	8	36.5000	1.3000	VIII	-	(Benouar)
							-	5.5	(Boughacha et al.)
							VIII	-	(Mokrane et al.)
1913	1	8	20	36	35.7000	-0.6000	-	4.7	(Boughacha et al.)
							VII	4.5	(Mokrane et al.)
1913	1	10	6	30	35.7000	-0.6000	III	-	(Benouar)
							-	4.7	(Boughacha et al.)
1913	2	26	3	51	35.6000	-0.5500	VI	4.2	(Benouar)
							-	4.7	(Boughacha et al.)
							V-VII	4.9	(Mokrane et al.)
1917	1	29	8	41	36.2000	3.5000	IV	4.9	(Benouar)
1920	2	25	17	56	35.5000	9.1000	VIII	5.9	(Benouar)
1920	10	7	7	12	36.5200	2.1450	VII	4.7	(Benouar)
							-	4.7	(Boughacha et al.)
							VII	4.6	(Mokrane et al.)
							VI	-	(Sebai & Ouahmed)
1921	9	25	0	0	36.6000	8.9000	VIII	-	(Benouar)
							-	5.5	(Boughacha et al.)
							-	4.8	(Benouar)
1921	10	22	21	18	34.0000	4.0000	-	4.8	(Boughacha et al.)
							-	4.8	(Benouar)
1922	8	25	11	47	36.3667	1.2567	VII	5.1	(Benouar)
							-	5.1	(Boughacha et al.)
							Mag $\geq$ 6.0	5.1	(Ayadi)
							VI	5.1-7.5	(Mokrane et al.)
1922	10	7	22	5	36.9000	9.9000	VII	4.7	(Benouar)
1922	11	19	17	4	36.3667	1.3667	IX	4.6	(Benouar)
							-	6.4	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1924	3	16	10	17	35.4667	5.8667	VIII	5.4-5.6	(Benouar)
							-	5.6	(Boughacha et al.)
							IX	5.6-6.5	(Mokrane et al.)
1924	5	11	0	0	36.6000	2.9000	VIII-IX	5.0	(Sebai & Ouahmed)
1924	7	19	12	48	36.4467	5.2800	VII	4.6	(Benouar)
							-	4.7	(Boughacha et al.)
							-	-	(Mokrane et al.)
1924	11	5	18	54	36.6233	3.6000	-	5.2	(Boughacha et al.)
							VIII-IX	5.0-6.5	(Mokrane et al.)
							VIII	4.8-5.2	(Benouar)
1924	11	6	5	5	36.6500	2.9000	VII	-	(Benouar)
							-	4.7	(Boughacha et al.)
1924	11	6	17	58	36.6500	2.9000	VII	4.7	(Benouar)
							-	4.7	(Boughacha et al.)
1925	2	20	22	0	36.6000	2.6700	VII	-	(Benouar)
							-	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1925	6	10	16	45	35.9133	2.6667	VI	4.9	(Benouar)
							-	4.8	(Boughacha et al.)
							VIII	4.9-5.7	(Mokrane et al.)
1925	9	30	13	25	34.0000	4.0000	-	4.8	(Benouar)
1926	10	15	6	48	35.7000	-2.7800	IV	5.0	(Benouar)
1927	1	20	21	33	36.5300	2.8300	VII	4.7	(Benouar)
							-	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
							VII	-	(Sebai & Ouahmed)
1928	6	2	8	39	36.7000	2.9000	VII	-	(Benouar)
							-	4.7	(Boughacha et al.)
							VII	-	(Sebai & Ouahmed)
							-	-	(Mokrane et al.)
1928	8	24	9	44	35.9233	0.8067	VIII	5.4	(Benouar)
							-	5.4	(Boughacha et al.)
							VIII	5.4-5.7	(Mokrane et al.)
1928	10	6	1	24	36.5000	1.3200	VII	-	(Benouar)
							-	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1928	12	3	5	30	36.4000	7.2000	-	4.9-5.0	(Benouar)
							-	4.9	(Boughacha et al.)
							VII	5.0-5.2	(Mokrane et al.)
1929	1	9	21	27	35.5300	-0.2000	VII	-	(Benouar)
							-	4.7	(Boughacha et al.)
1929	1	11	1	52	35.5000	-0.5000	VII	4.8	(Benouar)
							-	-	(Mokrane et al.)
1931	3	4	5	36	36.6000	2.7467	VIII	4.8	(Benouar)
							-	5.5	(Boughacha et al.)
							-	-	(Mokrane et al.)
1931	8	15	13	52	36.1000	3.6000	VIII	4.2-5.2	(Benouar)
							-	5.2	(Boughacha et al.)
							VIII-IX	5.7-6.5	(Mokrane et al.)
1931	11	2	14	58	36.4700	2.8300	VIII	4.6-5.7	(Mokrane et al.)
							VI	4.4-4.6	(Benouar)
1932	2	15	9	48	35.9000	2.9000	VII	4.7	(Benouar)
							-	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1932	3	5	2	10	37.5000	-2.7500	VIII	5.6	(Benouar)
							-	5.6	(Boughacha et al.)
1932	4	18	4	22	36.3000	2.8000	VII	4.7	(Benouar)
1934	9	7	3	39	36.2667	1.7100	VII	5.0-5.1	(Benouar)
							-	4.9	(Boughacha et al.)
							Mag $\geq$ 6.0	5.0	(Ayadi)
							IX	5.0-6.5	(Mokrane et al.)
1934	11	7	14	34	37.0000	2.0000	VII	5.0-5.2	(Mokrane et al.)
							III	4.5-4.6	(Benouar)
							VII	5.0	(Sebai & Ouahmed)
1935	3	6	3	30	36.9000	8.8700	VII	-	(Benouar)
							-	4.7	(Boughacha et al.)
1935	9	19	3	12	37.5000	7.0000	VI	4.9-5.1	(Benouar)
							-	4.9	(Boughacha et al.)
							-	5.1	(Mokrane et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1936	12	28	0	29	33.8000	6.8000	VI	4.9–5.0	(Benouar)
							–	4.8	(Boughacha et al.)
							–	4.9	(Mokrane et al.)
1937	2	10	18	16	36.4500	7.5000	VIII	5.2–5.4	(Benouar)
							–	5.4	(Boughacha et al.)
							VIII–IX	5.4–6.5	(Mokrane et al.)
1937	7	19	15	12	36.4000	2.4000	VII	4.7	(Benouar)
							–	–	(Mokrane et al.)
1938	3	2	7	43	36.4200	2.7500	VII	5.0	(Benouar)
							–	4.7	(Boughacha et al.)
							VII–VIII	5.2–5.7	(Mokrane et al.)
							VII	–	(Sebaï & Ouahmed)
1939	1	2	9	3	36.5300	–2.7500	–	3.2	(Benouar)
							–	4.7	(Boughacha et al.)
1939	4	1	8	3	35.9000	0.1000	VI–VII	4.6–5.2	(Mokrane et al.)
							VII	4.6	(Benouar)
1940	5	16	6	47	37.4000	–1.9000	–	4.7	(Benouar)
							–	4.7	(Boughacha et al.)
1940	5	28	10	15	36.8000	3.0300	III	5.0	(Benouar)
1940	9	18	7	13	34.6567	3.2500	VII	4.5–5.0	(Benouar)
							–	4.9	(Boughacha et al.)
							–	–	(Mokrane et al.)
1941	3	17	8	10	33.7000	0.5000	VI	4.7	(Benouar)
							VI	4.6	(Mokrane et al.)
1942	3	2	22	23	36.5000	3.8667	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							–	–	(Mokrane et al.)
1943	4	16	11	43	36.0200	4.3667	VIII	5.0–5.3	(Benouar)
							–	4.9	(Boughacha et al.)
							IX	5.0–6.5	(Mokrane et al.)
1943	6	7	12	37	36.0800	4.5500	VI	4.7	(Benouar)
1943	6	10	7	47	36.0800	4.5500	VI	5.0	(Benouar)
1946	2	12	2	43	35.7333	4.9067	VIII	5.6–6.2	(Benouar)
							–	5.6	(Boughacha et al.)
							Mag ≥ 6.0	5.6	(Ayadi)
							VIII–IX	5.6–6.5	(Mokrane et al.)
1946	9	9	17	26	36.3933	4.1033	VII	5.2–5.6	(Benouar)
							–	5.2	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1947	4	28	7	6	36.1900	1.2300	V	4.7	(Benouar)
1947	8	6	9	46	36.3033	6.6733	VIII	5.0–5.3	(Benouar)
							–	5.3	(Boughacha et al.)
							VIII–IX	5.3–6.5	(Mokrane et al.)
1947	8	7	12	29	36.3000	6.7000	–	5.0	(Benouar)
							–	5.0	(Boughacha et al.)
1947	10	27	10	29	37.6000	8.5000	VI	5.0	(Benouar)
							V–VI	–	(Mokrane et al.)
1948	3	13	8	6	32.9333	0.1000	IX	4.9–5.0	(Benouar)
							–	4.8	(Boughacha et al.)
							VIII	4.9	(Mokrane et al.)
1948	6	23	3	43	38.0000	–1.8000	VIII	4.9	(Benouar)
							–	4.9	(Boughacha et al.)
1949	1	15	11	14	36.5000	5.2500	V	4.7	(Benouar)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1949	2	17	21	0	36.5000	5.2500	VII	4.7–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
							VIII	4.9	(Mokrane et al.)
1949	3	31	1	48	37.0000	-2.3000	V	3.3	(Benouar)
							–	4.8	(Boughacha et al.)
1949	10	27	20	55	35.4200	0.2500	VI–VII	4.6–5.2	(Mokrane et al.)
							VI	–	(Benouar)
1950	4	20	17	19	33.9333	2.1000	VII	5.0–5.1	(Benouar)
							–	5.1	(Boughacha et al.)
							VII	5.1–5.2	(Mokrane et al.)
1952	5	20	13	18	37.8000	-1.2000	VII	4.8	(Benouar)
1953	7	5	4	4	36.2000	3.5000	VIII	4.6	(Benouar)
							–	5.5	(Boughacha et al.)
							VI–VII	5.7	(Mokrane et al.)
1953	8	22	1	8	36.0667	3.5333	VII	4.5–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
							VIII	4.5–5.7	(Mokrane et al.)
1953	8	29	14	8	35.8000	5.1333	VI	5.2	(Benouar)
							–	5.2	(Boughacha et al.)
							VIII–IX	5.2–6.5	(Mokrane et al.)
1953	10	17	19	33	35.6000	9.7000	VII	4.7	(Benouar)
1953	12	25	5	59	36.1800	3.5667	VII	4.8–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
							VII	4.8–5.2	(Mokrane et al.)
1954	9	9	1	4	36.3000	1.4700	X	6.7–7.0	(Benouar)
							–	6.7	(Boughacha et al.)
							Mag ≥ 6.0	6.7	(Ayadi)
							X–XI	6.7–8.4	(Mokrane et al.)
1954	9	9	1	49	36.0000	1.5000	X	5.0	(Benouar)
							–	5.0	(Boughacha et al.)
							Mag ≥ 6.0	6.7	(Ayadi)
							VI–X	6.7	(Mokrane et al.)
1954	9	9	2	52	36.2800	1.4700	VI	4.7	(Benouar)
							–	4.7	(Boughacha et al.)
							Mag ≥ 6.0	6.7	(Ayadi)
							VI–X	4.7	(Mokrane et al.)
1954	9	9	9	28	36.2800	1.4700	VI	4.7	(Benouar)
							–	5.1	(Boughacha et al.)
							Mag ≥ 6.0	6.7	(Ayadi)
							–	6.0	(Mokrane et al.)
1954	9	10	5	44	36.6000	1.3000	VIII	6.0–6.3	(Benouar)
							–	6.3	(Boughacha et al.)
							VIII–IX	5.7–6.5	(Mokrane et al.)
1954	9	16	22	18	36.1867	1.4800	VII	4.0–4.8	(Benouar)
							–	4.8	(Boughacha et al.)
							VIII	5.7	(Mokrane et al.)
1954	9	17	12	2	36.0000	1.5000	VIII	4.8–5.7	(Mokrane et al.)
							VIII	4.2	(Benouar)
1954	10	10	5	44	36.4800	1.3000	IX	6.0	(Benouar)
							–	6.0	(Boughacha et al.)
							VI	4.2–4.6	(Mokrane et al.)
1954	10	12	19	23	36.2500	1.7000	VII	6.0	(Benouar)
							VI–VII	4.6–5.2	(Mokrane et al.)



**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1955	2	4	5	12	36.4000	1.5800	VIII	4.8	(Benouar)
							VIII	4.8–5.7	(Mokrane et al.)
1955	3	14	5	7	35.5000	-0.7500	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1955	5	8	21	39	36.5650	1.4800	VII	4.9	(Benouar)
							VIII	4.9–5.7	(Mokrane et al.)
1955	6	5	14	56	36.3550	1.5500	VIII	5.8	(Benouar)
							VIII	5.2–5.7	(Mokrane et al.)
1955	9	13	9	39	36.5000	3.4000	VII	4.0	(Benouar)
							–	4.7	(Boughacha et al.)
							VI–VII	4.6–5.2	(Mokrane et al.)
							VII	–	(Sebaï & Ouahmed)
1955	12	24	13	6	36.4000	1.7000	VI	4.8	(Benouar)
							–	4.7	(Boughacha et al.)
							VI	4.6–4.8	(Mokrane et al.)
1956	2	14	9	53	36.5000	1.5000	VII	5.9	(Benouar)
							VII	5.2–5.9	(Mokrane et al.)
1956	5	23	0	5	36.4000	4.9000	VI	4.1–4.5	(Benouar)
							–	4.7	(Boughacha et al.)
							VI	4.6	(Mokrane et al.)
1956	5	23	6	37	36.4000	7.3000	VII–VIII	5.2–5.7	(Mokrane et al.)
							VIII	–	(Benouar)
1956	6	26	1	50	36.0000	8.1000	VII	4.2	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	5.2	(Mokrane et al.)
1957	1	23	23	7	36.3000	1.5000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VI	–	(Mokrane et al.)
1957	2	20	4	40	36.4000	9.0000	IX	5.1–5.6	(Benouar)
							–	5.1	(Boughacha et al.)
							–	5.6	(Mokrane et al.)
1957	6	28	21	23	36.1000	1.3900	VII	5.0	(Benouar)
							VII	5.0	(Mokrane et al.)
1957	8	15	20	42	36.0300	1.4200	VIII	4.7	(Benouar)
							VIII	–	(Mokrane et al.)
1957	10	19	6	8	36.4000	3.3750	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VI–VII	–	(Mokrane et al.)
							VII	–	(Sebaï & Ouahmed)
1957	11	13	19	16	36.2167	5.3933	VIII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII–VIII	–	(Mokrane et al.)
1957	11	21	19	16	36.2500	5.3800	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1957	11	26	22	55	36.2000	5.4000	V	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1957	12	2	12	48	36.5733	1.3600	VI	4.1	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1957	12	21	18	53	36.7800	1.5000	VI	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1957	12	22	19	5	36.6000	1.3000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1958	1	2	7	40	36.3000	1.8000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1958	1	5	3	7	36.3000	1.8000	III	–	(Benouar)
							–	4.7	(Boughacha et al.)
1958	1	26	8	34	36.5000	1.3000	VI	4.8	(Benouar)
							VI–VII	–	(Mokrane et al.)
1958	1	30	2	1	36.2667	1.7667	VII	3.0	(Benouar)
							–	4.7	(Boughacha et al.)
							VI–VI	–	(Mokrane et al.)
1958	2	6	3	56	36.3000	1.7000	VII	3.3	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1958	3	3	13	44	36.3000	2.8000	VII	3.3	(Benouar)
							–	4.7	(Boughacha et al.)
							VI–VII	–	(Mokrane et al.)
1959	5	24	13	19	36.2500	4.6133	VIII	4.5–4.8	(Benouar)
							–	5.5	(Boughacha et al.)
							VII–VIII	5.5	(Mokrane et al.)
1959	11	7	2	32	36.3550	2.4775	VIII	4.9–5.5	(Benouar)
							–	5.5	(Boughacha et al.)
							VIII–IX	5.5	(Mokrane et al.)
1959	12	12	20	0	35.7733	–0.5867	VIII	5.5	(Sebäi & Ouahmed)
							VII	4.3–4.5	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1960	2	20	20	33	36.3425	2.6250	VII	3.3	(Benouar)
							–	4.7	(Boughacha et al.)
							VI–VII	–	(Mokrane et al.)
							VI–VII	–	(Sebäi & Ouahmed)
1960	2	21	8	13	36.0133	4.0933	VIII	5.1–5.9	(Benouar)
							–	5.6	(Boughacha et al.)
							Mag ≥ 6.0	5.6	(Ayadi)
							VIII–IX	5.6	(Mokrane et al.)
1960	12	1	15	14	36.0333	2.0667	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VI–VII	–	(Mokrane et al.)
1961	12	2	12	40	36.5333	8.2600	–	5.2–5.5	(Benouar)
							–	5.2	(Boughacha et al.)
							–	5.5	(Mokrane et al.)
							–	5.5	(Boughacha et al.)
1962	2	18	7	0	36.4400	8.1800	VIII	5.3	(Benouar)
1962	3	20	19	15	35.7000	2.6667	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1962	11	5	8	29	37.5000	–2.8000	–	–	(Benouar)
1963	3	14	0	0	36.2000	6.0700	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1963	5	30	1	54	37.7000	–1.9000	V	4.7	(Benouar)
1963	6	27	11	45	37.2000	–2.2000	–	3.0–3.1	(Benouar)
							–	4.7	(Boughacha et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1963	9	4	5	6	36.0200	5.2700	–	5.6–6.3	(Benouar)
							–	6.3	(Boughacha et al.)
							–	5.7	(Mokrane et al.)
1963	9	4	8	37	36.0000	5.2000	–	4.7–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
1964	5	13	13	46	36.0000	-1.6500	VI	4.7	(Benouar)
							VII	4.7	(Mokrane et al.)
1964	6	9	2	33	37.8000	-2.6000	VIII	5.2	(Benouar)
							–	4.6	(ISC)
1964	7	13	12	25	36.7000	-2.0000	–	–	(Benouar)
1964	7	15	9	49	35.5500	4.4000	V	4.9	(Benouar)
							–	4.9	(Mokrane et al.)
							–	4.1	(ISC)
1965	1	1	21	38	35.6800	4.4275	–	4.9	(ISC)
							VII	5.1–5.5	(Benouar)
							–	5.2	(Boughacha et al.)
							Mag $\geq$ 6.0	5.5	(Ayadi)
							VIII	5.5	(Mokrane et al.)
1965	1	9	21	36	35.6000	4.6000	–	3.6–4.8	(Benouar)
							–	4.0	(ISC)
1965	1	15	23	47	35.7150	4.3600	VI	5.2	(Benouar)
							–	5.1	(Mokrane et al.)
							–	4.6	(ISC)
1965	2	21	2	20	35.5000	6.5000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1967	1	26	16	11	34.5900	10.4500	–	4.7	(ISC)
							VII	5.0	(Benouar)
1967	4	23	9	30	36.2560	2.4280	–	4.8	(ISC)
							VI	4.6–5.0	(Benouar)
							–	4.7	(Boughacha et al.)
							VI	4.8	(Sebäi & Ouahmed)
							VI–VII	4.4	(Mokrane et al.)
1967	4	27	1	54	35.7000	-0.2000	V	4.7	(Benouar)
							–	4.8	(Mokrane et al.)
1967	5	27	1	54	35.7067	-0.2400	–	4.7	(ISC)
							V	4.7	(Benouar)
							–	4.8	(Mokrane et al.)
1967	7	13	2	10	35.4950	-0.1200	–	4.9	(ISC)
							VII	4.7–5.2	(Benouar)
							–	4.8	(Boughacha et al.)
							VII–VIII	5.1	(Mokrane et al.)
1967	7	29	21	54	38.0000	-1.3000	–	–	(Benouar)
1968	1	4	6	42	37.6800	-2.4000	–	4.2–5.0	(Benouar)
							–	4.2	(ISC)
1968	2	25	15	40	36.6250	5.4050	–	4.8	(ISC)
							VII	4.5–5.9	(Benouar)
							–	4.8	(Boughacha et al.)
							VII–VIII	4.9	(Mokrane et al.)
1968	7	29	18	10	35.2000	-2.2000	–	3.9–4.9	(Benouar)
							–	–	(Mokrane et al.)
1969	1	26	14	26	35.6000	6.0000	–	4.7	(Mokrane et al.)
							–	4.6	(ISC)
							–	4.0–4.6	(Benouar)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1970	6	28	13	40	35.8000	11.6000	–	4.9	(ISC)
							–	4.5	(Benouar)
1970	12	1	1	2	36.9800	9.8000	–	4.9	(ISC)
							VIII	5.1	(Benouar)
1971	2	23	7	15	36.0632	1.6382	IV	3.0–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1972	3	16	21	31	37.4200	-2.3100	VII	4.8	(Benouar)
							–	4.6	(ISC)
1972	5	21	23	15	34.3200	8.4000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1972	5	21	23	30	34.3200	8.4000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1972	5	22	3	5	34.3200	8.4000	VII	–	(Benouar)
							–	4.7	(Boughacha et al.)
1972	8	14	14	6	35.0600	-2.7800	V	4.8	(Benouar)
1972	11	20	14	22	37.8000	-1.5100	–	3.8–4.7	(Benouar)
1972	12	17	19	6	34.7900	-2.7700	–	3.7–5.0	(Benouar)
1973	8	24	10	50	35.8800	-0.9950	–	4.0–5.0	(Benouar)
1973	8	24	15	57	35.8500	-0.4000	–	3.3–4.8	(Benouar)
1973	11	24	14	5	36.0586	4.4696	–	4.9	(ISC)
							VII	4.9–5.0	(Benouar)
							–	4.8	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1973	11	24	15	22	36.0586	4.4696	–	4.9	(ISC)
							VII	4.9–5.1	(Benouar)
							–	4.8	(Boughacha et al.)
							Mag ≥ 6.0	5.1	(Ayadi)
1973	11	25	4	20	36.1413	4.4703	–	4.7	(ISC)
							–	4.4–4.7	(Benouar)
							–	4.8	(Boughacha et al.)
1974	1	28	3	39	36.0737	4.4548	–	4.7	(ISC)
							–	4.8	(Mokrane et al.)
							–	4.7	(Benouar)
1974	6	28	11	9	36.5465	5.2730	–	5.0	(ISC)
							–	4.6–5.0	(Benouar)
							–	4.9	(Boughacha et al.)
							V	–	(Mokrane et al.)
1974	6	29	1	6	36.4806	5.2055	–	4.7	(ISC)
							–	4.7	(Mokrane et al.)
							–	4.6–4.7	(Benouar)
1974	7	13	15	57	35.9596	4.7933	–	4.8	(ISC)
							–	4.6–4.8	(Benouar)
							–	4.7	(Boughacha et al.)
							–	4.8	(Mokrane et al.)
1974	7	28	0	0	36.2500	5.4800	VII	5.0	(Benouar)
1975	3	18	21	25	36.7500	-2.6000	III	4.7	(Benouar)
1975	7	20	10	49	36.5205	2.9437	–	4.7–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
							VI	–	(Mokrane et al.)
							VI	4.9	(Sebaï & Ouahmed)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1975	10	30	21	18	35.9610	3.7998	V	5.1–5.4	(Benouar)
							–	5.4	(Boughacha et al.)
							IV	–	(Mokrane et al.)
1977	1	19	20	46	36.5350	8.4600	VII	4.6–4.9	(Benouar)
							–	5.1	(Boughacha et al.)
							IV	–	(Mokrane et al.)
1977	2	9	13	55	36.4200	8.4700	VII	4.2–4.5	(Benouar)
							–	4.8	(Boughacha et al.)
1977	4	12	19	45	37.0300	-0.4400	–	4.7	(Benouar)
1977	4	14	7	17	36.3567	5.6900	V	4.3–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
							V	–	(Mokrane et al.)
1978	2	8	16	14	34.2700	9.1500	–	5.0	(ISC)
							VII	5.0	(Benouar)
1978	5	10	23	54	37.5200	-2.1700	–	–	(Benouar)
1978	12	11	8	56	33.3400	.0200	–	4.9	(ISC)
							–	–	(Mokrane et al.)
							–	4.1–4.9	(Benouar)
1979	4	9	8	13	37.1400	10.1200	–	4.8	(ISC)
							VII	4.8	(Benouar)
1980	10	10	12	25	36.1650	1.4325	–	6.3	(ISC)
							X	6.3–7.5	(Benouar)
							–	7.3	(Boughacha et al.)
							Mag $\geq$ 6.0	7.3	(Ayadi)
							IX	7.2	(Mokrane et al.)
1980	10	10	12	37	36.3225	1.5675	–	5.6	(ISC)
							–	4.9–5.6	(Benouar)
							–	5.6	(Boughacha et al.)
							–	–	(Mokrane et al.)
1980	10	10	14	44	36.3075	1.4275	–	5.4	(ISC)
							–	4.6–5.4	(Benouar)
							–	5.4	(Boughacha et al.)
							–	–	(Mokrane et al.)
1980	10	10	15	36	36.4100	1.7000	–	4.8	(ISC)
							–	4.2–4.8	(Benouar)
							–	4.7	(Boughacha et al.)
1980	10	10	15	39	36.2450	1.5925	–	6.0	(ISC)
							–	6.0–6.1	(Benouar)
							–	6.0	(Boughacha et al.)
							–	–	(Mokrane et al.)
1980	10	10	17	32	36.1300	1.4000	–	5.4	(ISC)
							–	4.8–5.4	(Benouar)
							–	4.7	(Boughacha et al.)
							–	5.2	(Mokrane et al.)
1980	10	10	19	08	36.4200	1.5200	–	4.5–5.4	(Benouar)
							–	5.4	(ISC)
							–	5.0	(Mokrane et al.)
1980	10	13	6	37	36.3300	1.5625	–	5.2	(ISC)
							–	5.2	(Benouar)
							–	5.2	(Boughacha et al.)
							–	5.0	(Mokrane et al.)



**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1980	10	14	17	34	36.3500	1.6800	–	5.1	(ISC)
							–	–	(Mokrane et al.)
							–	4.4–5.1	(Benouar)
1980	10	22	16	23	36.4900	1.4933	–	5.0	(ISC)
							–	4.2–5.0	(Benouar)
							–	4.9	(Boughacha et al.)
1980	10	30	23	38	36.3600	1.6500	–	5.3	(ISC)
							–	4.6–5.3	(Benouar)
1980	11	8	7	54	36.1200	1.3800	–	5.4	(ISC)
							–	4.9–5.4	(Benouar)
							–	5.0	(Boughacha et al.)
1980	11	10	0	1	36.5400	1.3800	–	4.9	(ISC)
							–	4.1–4.9	(Benouar)
1980	12	3	10	31	36.4800	1.6000	–	4.8	(ISC)
							–	4.8	(Benouar)
							–	4.9	(Boughacha et al.)
1980	12	5	13	32	35.9700	1.3400	–	5.1	(ISC)
							–	4.9–5.1	(Benouar)
							–	4.9	(Boughacha et al.)
1980	12	7	17	37	36.0600	1.3000	–	5.3	(ISC)
							–	5.3–5.7	(Benouar)
							–	5.7	(Boughacha et al.)
1980	12	31	2	25	36.0750	1.3000	–	4.7	(ISC)
							–	4.3–4.7	(Benouar)
1981	1	15	4	25	36.3467	1.6267	–	5.2	(ISC)
							–	5.2	(Mokrane et al.)
							–	4.6–5.2	(Benouar)
1981	1	17	21	4	33.8900	8.1300	–	4.7	(ISC)
							–	4.5–4.7	(Benouar)
1981	1	31	16	29	36.3640	1.6580	–	4.8	(ISC)
							–	4.7	(Mokrane et al.)
							–	4.6–4.7	(Benouar)
1981	2	1	13	19	36.4300	1.6800	–	5.5	(ISC)
							–	5.4–5.5	(Benouar)
							–	5.4	(Boughacha et al.)
							–	5.5	(Mokrane et al.)
1981	2	1	23	0	36.4500	1.7000	–	4.9	(ISC)
							–	4.6–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
1981	2	5	9	12	36.4000	1.5300	–	4.8	(ISC)
							–	–	(Benouar)
1981	2	14	13	15	35.8950	1.2575	–	5.0	(ISC)
							–	5.0	(Benouar)
							–	4.8	(Boughacha et al.)
							–	5.0	(Mokrane et al.)
1981	3	29	8	57	36.7000	1.8200	–	4.8	(ISC)
							–	3.8–4.8	(Benouar)
1981	4	19	19	50	35.9900	–0.2200	VI	–	(Mokrane et al.)
							–	3.4–4.6	(Benouar)
1981	4	21	17	19	36.3500	1.5800	–	4.8	(ISC)
							–	4.6–4.8	(Benouar)
							–	4.7	(Boughacha et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1981	9	25	9	23	36.3833	1.5133	–	4.8	(ISC)
							–	5.1	(Mokrane et al.)
							–	4.4–4.8	(Benouar)
1982	9	11	21	35	36.3600	1.6800	–	4.9	(ISC)
							VI	–	(Mokrane et al.)
1982	11	15	20	7	35.5500	1.3600	–	5.0	(ISC)
							–	4.8–5.0	(Benouar)
							–	4.7	(Boughacha et al.)
							VII	–	(Mokrane et al.)
1983	1	6	21	55	36.6300	-2.2300	–	5.0	(ISC)
							III	4.2–5.0	(Benouar)
							–	4.9	(Boughacha et al.)
1983	3	20	6	59	36.4800	-2.1400	–	4.7	(ISC)
							IV	4.7	(Benouar)
1984	3	31	4	45	36.4600	1.7100	–	4.8	(ISC)
							–	3.8–4.8	(Benouar)
							–	4.7	(Boughacha et al.)
							IV	–	(Mokrane et al.)
1984	6	15	23	2	36.5000	1.5700	–	4.7	(ISC)
							–	4.0–4.7	(Benouar)
1984	9	13	4	34	37.0700	-2.4000	–	4.7	(ISC)
							V	5.0	(Benouar)
1984	10	5	6	37	36.0275	6.8350	–	4.8	(ISC)
							IV	4.6–4.8	(Benouar)
							–	4.7	(Boughacha et al.)
							VI	–	(Mokrane et al.)
1985	3	5	15	37	35.5600	1.4300	–	4.9	(ISC)
							–	4.6–4.9	(Benouar)
							VI	–	(Mokrane et al.)
1985	9	7	9	51	36.0500	1.1700	–	4.7	(ISC)
							–	4.0–4.7	(Benouar)
							V	–	(Mokrane et al.)
1985	10	27	19	34	36.3875	6.8000	–	5.4	(ISC)
							VIII	5.4–5.7	(Benouar)
							–	5.9	(Boughacha et al.)
							Mag $\geq$ 6.0	5.9	(Ayadi)
							VIII	–	(Mokrane et al.)
1986	3	28	2	56	36.3700	6.8200	–	4.8	(ISC)
							–	4.6–4.8	(Benouar)
							–	4.7	(Boughacha et al.)
							V	–	(Mokrane et al.)
1987	1	26	11	11	35.9190	1.3810	–	5.0	(ISC)
							VII	–	(Mokrane et al.)
							–	4.4–5.0	(Benouar)
1987	9	16	22	0	36.9300	3.6148	–	4.7	(ISC)
							VI	4.7	(Sebaï & Ouahmed)
							VI	–	(Mokrane et al.)
							–	4.1–4.7	(Benouar)
1988	6	24	7	43	34.2400	9.2100	–	3.9–4.8	(Benouar)
							–	4.6	(ISC)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1988	10	31	10	12	36.4275	2.5975	–	5.3–5.6	(Benouar)
							–	5.6	(Boughacha et al.)
							Mag ≥ 6.0	5.4	(Ayadi)
							VII	–	(Mokrane et al.)
							VII	5.5	(Sebäi & Ouahmed)
1989	1	3	16	52	35.5982	11.6024	–	5.1	(ISC)
							–	4.7–5.1	(Benouar)
1989	1	6	5	26	35.5923	11.6611	–	5.1	(ISC)
							–	4.7–5.1	(Benouar)
1989	1	9	10	2	35.6482	11.6184	–	5.1	(ISC)
							–	4.3–5.1	(Benouar)
1989	4	11	13	49	34.8899	9.1422	–	4.9	(ISC)
							–	4.1–4.9	(Benouar)
1989	10	29	19	21	36.7099	2.4135	–	5.6	(ISC)
							VII	5.5–5.6	(Benouar)
							–	6.0	(Boughacha et al.)
							Mag ≥ 6.0	6.0	(Ayadi)
							–	6.0	(Mokrane et al.)
							VIII	6.0	(Sebäi & Ouahmed)
1989	11	5	11	38	36.7192	2.4218	–	4.7	(ISC)
							–	4.5–4.7	(Benouar)
1990	2	9	9	31	36.7800	2.4800	–	5.0	(ISC)
							–	4.7–5.0	(Benouar)
							–	4.7	(Boughacha et al.)
1990	4	12	22	47	36.7900	2.4900	–	4.7	(ISC)
							–	4.1–4.7	(Benouar)
1990	12	29	19	10	36.0400	11.0800	–	4.7	(ISC)
1991	8	8	22	46	35.6500	11.6400	–	4.7	(ISC)
							–	4.4–4.7	(Benouar)
1992	1	19	21	20	36.2142	1.7875	–	4.9	(ISC)
							V–VI	5.2	(Mokrane et al.)
							–	4.6–4.9	(Benouar)
1992	3	12	13	5	35.2905	–2.5412	–	5.2	(ISC)
							–	5.1–5.2	(Benouar)
							–	5.1	(Boughacha et al.)
1992	3	13	0	37	35.2901	–2.4314	–	4.9	(ISC)
							–	4.7–4.9	(Benouar)
							–	4.8	(Boughacha et al.)
1992	6	12	19	16	34.1989	8.3294	–	5.2	(ISC)
							–	4.8–5.2	(Benouar)
							–	4.8	(Boughacha et al.)
							VII–VIII	–	(Mokrane et al.)
1992	10	17	20	43	35.2809	–1.5184	–	5.0	(ISC)
							–	4.8–5.0	(Benouar)
							–	4.9	(Boughacha et al.)
							V	4.3	(Mokrane et al.)
1993	5	23	7	40	35.3488	–2.4988	–	5.3	(ISC)
							–	5.0–5.3	(Benouar)
							–	5.0	(Boughacha et al.)
1994	1	4	89	3	36.6229	–2.8082	–	4.9	(ISC)
							–	4.8–4.9	(Benouar)
							–	4.9	(Boughacha et al.)

**Table 2** continued

Western Tellian Atlas: Lat min = 34.4; Lat max = 36.75; Long min = -2.82; Long max = 2.0

Central Tellian Atlas: Lat min = 35.0; Lat max = 38.00; Long min = 2.00; Long max = 5.0

Eastern Tellian Atlas: Lat min = 33.0; Lat max = 38.00; Long min = 5.00; Long max = 11.9

1994	8	18	1	13	35.5062	-1.1105	-	5.5	(ISC)
							-	5.5-5.8	(Benouar)
							-	5.9	(Boughacha et al.)
1994	9	17	4	56	36.4776	9.1610	-	5.2	(ISC)
							-	4.5-5.2	(Benouar)
1994	12	31	19	1	36.3621	2.4602	-	4.7	(ISC)
							-	4.5-4.7	(Benouar)
1995	1	31	15	40	35.6500	-0.2300	-	4.8	(ISC)
							-	4.6-4.8	(Benouar)
1995	9	22	11	20	35.3600	8.2133	-	4.7	(ISC)
							-	4.7-5.1	(Benouar)
							-	5.4	(Boughacha et al.)
1996	4	18	21	58	36.2641	4.6525	-	4.9	(ISC)
							-	4.7	(Boughacha et al.)
1996	9	4	4	14	36.9749	2.8889	-	5.3	(ISC)
							-	5.5	(Boughacha et al.)
1997	3	20	18	2	33.9800	8.2650	-	5.0	(ISC)
							-	5.2	(Boughacha et al.)
1998	12	3	16	35	36.1803	8.7796	-	4.6	(ISC)
							-	5.1	(Boughacha et al.)
1999	12	22	17	36	35.3055	-1.2975	-	5.3	(ISC)
							-	5.7	(Boughacha et al.)
2000	8	18	18	15	36.1945	4.9625	-	4.9	(ISC)
							-	5.2	(Boughacha et al.)
2000	8	18	18	15	36.1615	5.0130	-	4.9	(ISC)
							-	5.2	(Boughacha et al.)
2000	11	10	20	10	36.5750	4.7700	-	5.8	(ISC)
							-	5.9	(Boughacha et al.)
2000	11	16	11	33	36.6465	4.7730	-	4.8	(ISC)
							-	4.8	(Boughacha et al.)
2002	2	4	20	9	37.1710	-2.6660	-	4.9	(ISC)
2002	4	5	15	27	36.7600	6.9560	-	5.0	(ISC)
2002	6	24	1	20	35.9230	9.8750	-	4.7	(ISC)
2003	1	1	0	55	36.2649	2.8890	-	4.7	(ISC)
2003	5	21	18	44	36.9853	3.6597	-	6.3	(ISC)
2003	5	21	18	51	37.0947	3.5864	-	5.5	(ISC)
2003	5	21	19	2	37.1105	3.5993	-	5.0	(ISC)
2003	5	22	3	14	37.1550	3.5724	-	5.2	(ISC)
2003	5	22	13	57	37.1215	3.8371	-	4.8	(ISC)
2003	5	27	17	11	36.9377	3.5367	-	5.5	(ISC)
2003	5	28	6	58	36.9976	3.1517	-	4.8	(ISC)
2003	5	29	2	15	36.8950	3.2553	-	4.8	(ISC)
2004	2	24	2	33	35.3900	-1.9640	-	4.8	(ISC)
2005	2	7	20	5	36.0970	10.9070	-	4.7	(ISC)
2005	2	7	20	46	36.2250	10.8740	-	4.9	(ISC)
2006	3	20	19	44	34.3050	5.0980	-	5.2	(ISC)
2006	3	20	19	44	36.8479	5.3727	-	5.0	(ISC)
2006	4	2	6	44	35.1029	3.9729	-	5.0	(ISC)
2006	8	7	10	51	35.2032	3.9257	-	4.8	(ISC)
2006	10	26	14	28	37.7910	11.5080	-	4.8	(ISC)
2006	12	30	23	50	34.6782	3.4020	-	4.7	(ISC)
2007	2	14	15	24	36.4879	4.8834	-	4.7	(ISC)

Table 3  
Source parameters of recent major earthquakes that have occurred in the Tellian Atlas

Time and location of the earthquake	Magnitude	Depth Z (km)	Length L (km)	Maximal slip $D_{\max}$ (m)	Slope $\theta$ ( $^{\circ}$ )	$M_0$ min_waves (dynes-cm) from waves
Orléanville (El-Asnam, Chleff) Sept. 1954	6.7	15	20 (BENOUAR, 1994)	2.5 (BENOUAR, 1994)	61	
Agadir Feb. 1960	5.7	9		0.36 (BENOUAR, 1994)		
Chleff (El-Asnam, Orléanville) Oct. 1980	7.3	15	40	6.6 (BEZZEGHOUD, 1988)	50	$2.6 \times 10^{26}$
Constantine Aug. 1908	5.5	10	18 (BOUNIF <i>et al.</i> , 1987)	0.4 (BENOUAR, 1994)	80-90	
Constantine Oct. 1985	6.0	10	4 from surf. rup. 10 from aftershocks mapping (see text)	0.1	80-90	$5.2 \times 10^{24}$
Chenoua, Tipaza Oct. 1989	6.0	10		0.07	60	$1.1 \times 10^{24}$
Beni-Chougrane, Mascara, Aug. 1994	5.6	$\approx 10$ (AYADI <i>et al.</i> , 2002)		$\approx 0.57$ Evaluated from $M_0$	$\approx 65$	$4.9 \times 10^{24}$
Ain-Benian, Alger Sept. 1996	5.6					
Ain-Temouchent Dec. 1999	5.5	8 (BOUGHACHA, 2003)			50	$2.95 \times 10^{24}$ USGS $1.7 \times 10^{24}$
Boumerdès May 2003	6.8	15	28.5 (BOUNIF <i>et al.</i> , 2004)	2 from $M_0$ wave/( $\mu\text{A}$ )	45-50	$2.86 \times 10^{26}$ (YELLES <i>et al.</i> , 2004) $(\text{DELOUIS } et al., 2004)$
Time and location of the earthquake	$M_0$ max_waves (dynes-cm) from waves	$M_0$ field (dynes-cm) from field measure.	Focal mechanism	Stress drop $\Delta\sigma$ (bars)	Observations	
Orléanville (El-Asnam, Chleff) Sept. 1954		$3.3 \times 10^{26}$	46°N. Thrust faulting dipping toward N	35		
Agadir Feb. 1960						
Chleff (El-Asnam, Orléanville) Oct. 1980	$3.7 \times 10^{26}$ (OUYED, 1981; DESCHAMPS <i>et al.</i> , 1982)	$1.74 \times 10^{27}$ (OUYED, 1981; MEGHRAOUI, 1982)	57°N. Thrust faulting dipping toward N	46	$M_0$ wave is under estimated. $M_0$ field more reliable. (see text)	
Constant. Aug. 1908						
Constantine Oct. 1985	$6 \times 10^{24}$	$3.38 \times 10^{22}$ $5.94 \times 10^{24}$	57°N. strike-slip faulting	3.3 2.1	(BENOUAR, 1994) (BOUGHACHA, 2003; BOUNIF <i>et al.</i> , 1987) (BOUNIF <i>et al.</i> , 2003)	
Chenoua, Tipaza Oct. 1989	$9.6 \times 10^{24}$	$8.53 \times 10^{23}$ field defor $2.67 \times 10^{24}$ from aftershocks mapping	71°N. Thrust faulting dipping toward N	2.1		
Beni-Chougrane, Mascara, Aug. 1994			N71° Thrust faulting dipping toward N	79	Consistent with Ain-Temouchent in terms of stress drop (AYADI <i>et al.</i> , 2002)	
Ain-Benian, Alger Sept. 1996			N70° Thrust faulting + strike slip			
Ain-Temouchent Dec. 1999	$4.7 \times 10^{24}$		N57° Thrust faulting dipping toward S	105	Overall consistency with empirical relation	
Boumerdès May 2003	$2.86 \times 10^{26}$ (YELLES <i>et al.</i> , 2004)	$3.68 \times 10^{26}$ if $D_{\max} \approx 2 \text{ m} = M_0$ wave/( $\mu\text{A}$ ) $2 \text{ m} = M_0$ wave/( $\mu\text{A}$ ) $6.44 \times 10^{26}$ if $D_{\max} \approx 3.5 \text{ m}$ from the empirical relat.	N54° Thrust faulting dipping toward N	19 if $D_{\max} \approx 2 \text{ m} = M_0$ wave/( $\mu\text{A}$ ) 34 if $D_{\max} \approx 3.5 \text{ m}$ From the empirical relat.	Overall consistency. $D_{\max} \approx 3.5 \text{ m}$ is the possible displ. because $\Delta\sigma$ consistent	



ruptures has to be of about the same order of magnitude as the seismic moment evaluated from the seismogram;

2. the stress drop  $\Delta\sigma$  computed with the measured surface rupture characteristics, given by Eq. 1, must be approximately the same as the stress drop deduced from the measured seismic moment  $M_0$  given by Eq. 2 (KANAMORI and ANDERSON, 1975).

$$\Delta\sigma = C\mu D_{\max}/L, \quad (1)$$

$$\text{Log}(\Delta\sigma) = \text{log}(M_0) - 1.5 \text{log}(A) - \text{log}(C') \quad (2)$$

with

- $A$ : Fault plane area  
 $D_{\max}$ : Maximal displacement along the fault  
 $L$ : Length of the fault  
 $\mu$ : Crustal rocks rigidity coefficient

The stress drop, by opposition to the seismic moment, involves an independent observational constant  $C$  or  $C'$  that depend on the deformation mode, and therefore constitute another independent check relative to the reliability of the field mapping parameters.

$C$  and  $C'$ : constants that are dependent on the nature of the deformation:

- Dip-slip (normal fault or reverse fault)  $C \approx 0.84$  and  $C' \approx 1.18 \times (W/L)^{0.5}$

with

- $L$ : Length of the fault  
 $W$ : Fault plane width

if  $D/L < 0.00001$  then  $L \equiv W = Z/\sin(\theta)$

- $Z$ : Fault plane depth  
 $\theta$ : Fault plane dip

- Strike-slip  $C \approx 0.64$  and  $C' \approx 1.57 \times (W/L)^{0.5}$
- Circular fault  $\approx 1.37$  and  $C' \approx 0.4$

The empirical relations between  $m_b$  and sources parameters are obtained using the following formulas (KANAMORI and ANDERSON, 1975):

$$\text{log}(A) = m_b + a \quad (3)$$

$$\text{log}(M_0) = cm_b + d, \quad (4)$$

$$m_b = e \text{log}(L) + f, \quad (5)$$

$$\text{log}(D_{\max}) = gm_b + h, \quad (6)$$

where  $a$ ,  $c$ ,  $d$ ,  $e$ ,  $f$ ,  $g$  and  $h$  are the constants characterizing the seismotectonic properties of the studied region.

#### 4. Methodology

We established an algorithm to obtain the unknown constants  $a$ ,  $c$ ,  $d$ ,  $e$ ,  $f$ ,  $g$  and  $h$  (Table 4), thus allowing to advance past earthquake source parameters from the magnitude  $m_b$ .

Thus the cumulative seismic moment versus time  $\text{Sum}_{M_0}(t)$  and the cumulative absorbed displacement versus time  $\text{Sum}_D(t)$  will be obtained over a considerably larger time scale.

In the next sections it will be shown, on the basis of  $\text{Sum}_{M_0}(t)$  and  $\text{Sum}_D(t)$  and various other geological and geophysical observations, that the Tellian Atlas large-scale deformation is accommodated by three distinct decoupled tectonic blocks.  $\text{Sum}_{M_0}(t)$  and  $\text{Sum}_D(t)$  developed separately for the three distinct Tellian Atlas tectonic blocks provide precious information as to how the convergence between the African and Eurasian plates is accommodated from west to east. This has tremendous implications for seismic risk assessment.

Finally, recurrence times of large earthquake are theoretically estimated using Molnar and Kostrov formalisms, and compared to the historical and instrumental seismicity.

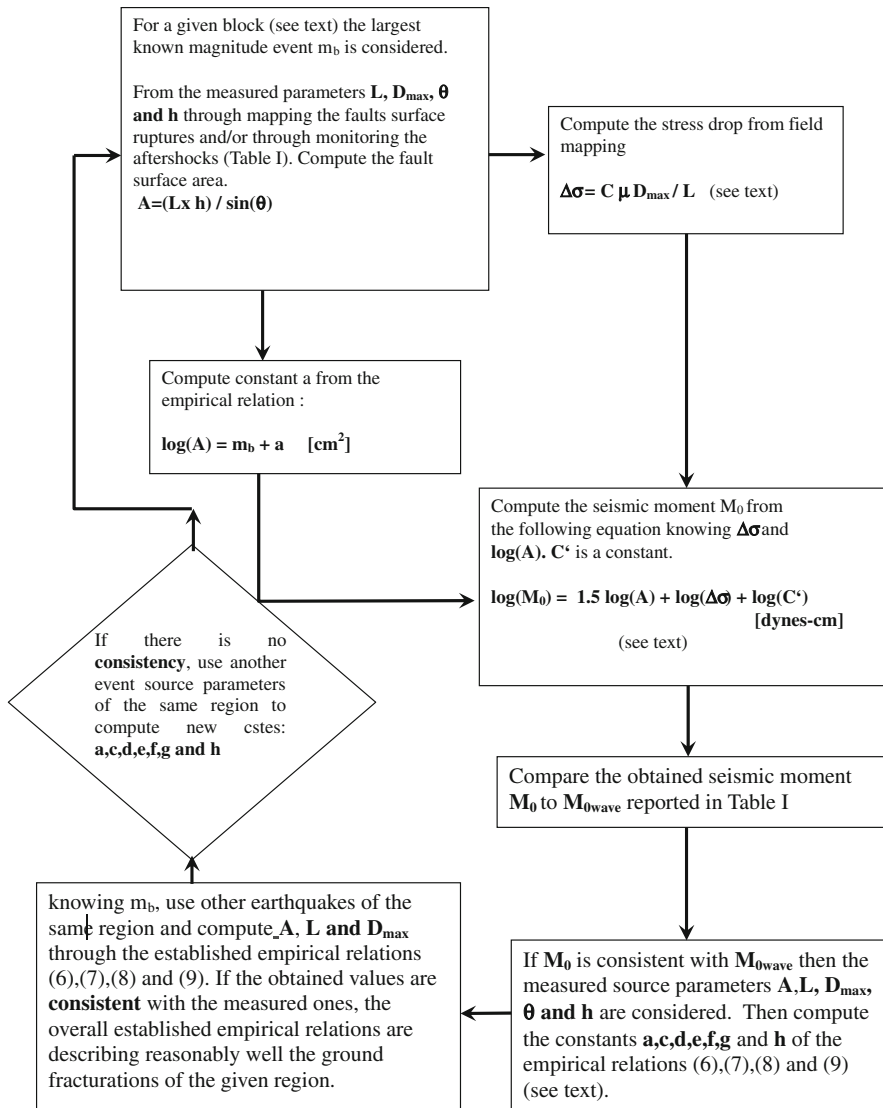
##### 4.1. Molnar and Kostrov Formalisms

###### 4.1.1 Molnar Formalism

To have an idea about the time  $T(M_0)$  necessary to nucleate an earthquake of a given seismic moment  $M_0$  one can use Molnar theoretical formalism (MOLNAR, 1979), based on the Gutenberg relation tying the observed number  $N$  of earthquakes of magnitudes larger or equal to  $m_b$  for a given region (Eq. 7), in which constants  $a'$  and  $b'$  reflect the seismotectonic characteristics of the region. Since the magnitude does not quantify accurately the seismic source, the magnitude  $m_b$  is substituted in the Gutenberg relation by its corresponding seismic moment  $M_0$  using Eq. (8).

Table 4

Flow Chart and Procedure to determine constants of Kanamori and Anderson's equations (see text)



$$\log(N) = a' - b'm_b, \tag{7}$$

$$\log(M_0) = cm_b + d. \tag{8}$$

On the basis of Eqs. 7 and 8 MOLNAR (1979) deduces  $T(M_0)$ , the time necessary to nucleate an earthquake of seismic moment  $M_0$ :

$$T(M_0) = \frac{M_0^\beta M_{0max}^{(1-\beta)}}{(1-\beta)\dot{M}_\Sigma}, \tag{9}$$

where

$M_{0max}$  is the maximal seismic moment ever recorded in the studied region;

The constant  $\beta = b'/c$ , in which  $b'$  and  $c$  are given by Eqs. 7 and 8 respectively;

$\dot{M}_\Sigma = \text{Sum}_M(t) / \Delta t$ , is the seismic moment rate of the region, in which  $\Delta t$  is the time length of the studied period.

This formalism can be used independently of the tectonic context.

#### 4.1.2 Kostrov Formalism

This formalism quantifies the strain rate  $\dot{\epsilon}$  of a given region on the basis of its seismic activity (KOSTROV, 1974).

$$\dot{M} = \mu \dot{\epsilon} \text{ volume}, \quad (10)$$

where  $\mu$  is the crustal rigidity coefficient of the volume (volume) of rocks under brittle deformation.

In the case of thrust faulting dipping about  $45^\circ$  and mainly oriented east–west, such as in the El-Asnam region, Eq. 10 may be expressed as follows (ANDERSON, 1979):

$$\dot{M} = 2\mu A \bar{V}, \quad (11)$$

where  $A$  is the fault surface area, and  $\bar{V}$  the average plate convergence velocity.

This formalism given by Eq. 10 is used when the tectonic context corresponds to a set of faults with arbitrary orientations.

#### 4.1.3 Other Data

Finally, other geological data such as Quaternary fault mapping (MEGHRAOUI, 1988), Maghreb digital topography and Landsat images, as well as Maghreb tectonic and physio-geographic maps (TAPPONNIER, 1977; BEAUCHAMP, 1998) have been integrated to give further physical insight to the observed graphs  $\text{Sum}_M(t)$ ,  $\text{Sum}_D(t)$ ,  $\frac{\Delta \text{Sum}_D(t)}{\Delta t}$ , and computed velocity  $V(t)$ , for each distinct tectonic block.

### 5. Tellian Atlas Empirical Relations

Since the 1980 El-Asnam earthquake is the most and best studied Algerian earthquake, we estimated the constants of the empirical relations (3)–(6), between the source parameters and magnitude of this event, and show that they apply well for the five other western and central Tellian Atlas earthquakes of Table 3.

#### 5.1. 1980 El-Asnam Seismic Moment

The most recently computed seismic moments for the 1980 El-Asnam earthquake, using waveforms

inversion (BEZZEGHOUD, 1988, Table 3; CMT Harvard Catalogue, Table 1) lead to  $2.6 \times 10^{26}$  and  $5.07 \times 10^{26}$  dyne-cm, respectively.

This earthquake has the most clearly mapped surface rupture and best studied aftershock sequence, and therefore the computed fault parameters can be considered as reliable (Tables 1, 3). The computed seismic moment from the following Eq. 12 using the parameter values of Tables 1 and 3, leads to  $1.7 \times 10^{27}$  dynes-cm.

$$M_0 = \mu D_{\max} A = \mu D_{\max} LZ / \sin(\theta) \quad (12)$$

- $\mu$ : Crustal rock rigidity  $\sim 3.3 \times 10^{11}$  (dynes-cm<sup>-2</sup>)
- $L$ : Length of the fault plane (cm)
- $Z$ : Depth of the aftershock seismicity (cm)
- $\theta$ : Slope of the fault plane, evaluated either from the aftershocks seismicity mapping or from focal mechanism (deg)

The theoretical formulas in both Brune circular dislocation and crack propagation models involve an average theoretical displacement (KANAMORI and ANDERSON, 1975). Practically, however, in the field the average displacement along a fault depends strongly on the number of points at which the displacement has been measured. It is therefore more meaningful to consider the largest displacement measured along the fault. Hence, if one computes the seismic moment using the maximal measured displacement, the resulting seismic moment will be an upper bound value. Another assumption is that the measure of the fault length from the seismic aftershock area is based on the distance between the largest events located at the two ends of the fault, and inside the aftershock cloud. It is therefore a matter of appreciation, especially when the event locations are obtained from data of a network that does not adequately surround the seismogenic area. MEGHRAOUI (1982), from the evaluation of the field displacements measured after the 1980 El-Asnam earthquake, gives 6 and 2.7 m as the largest vertical and horizontal displacements, respectively. It follows that the largest measured displacement used in formula (6) is about 6.6 m.

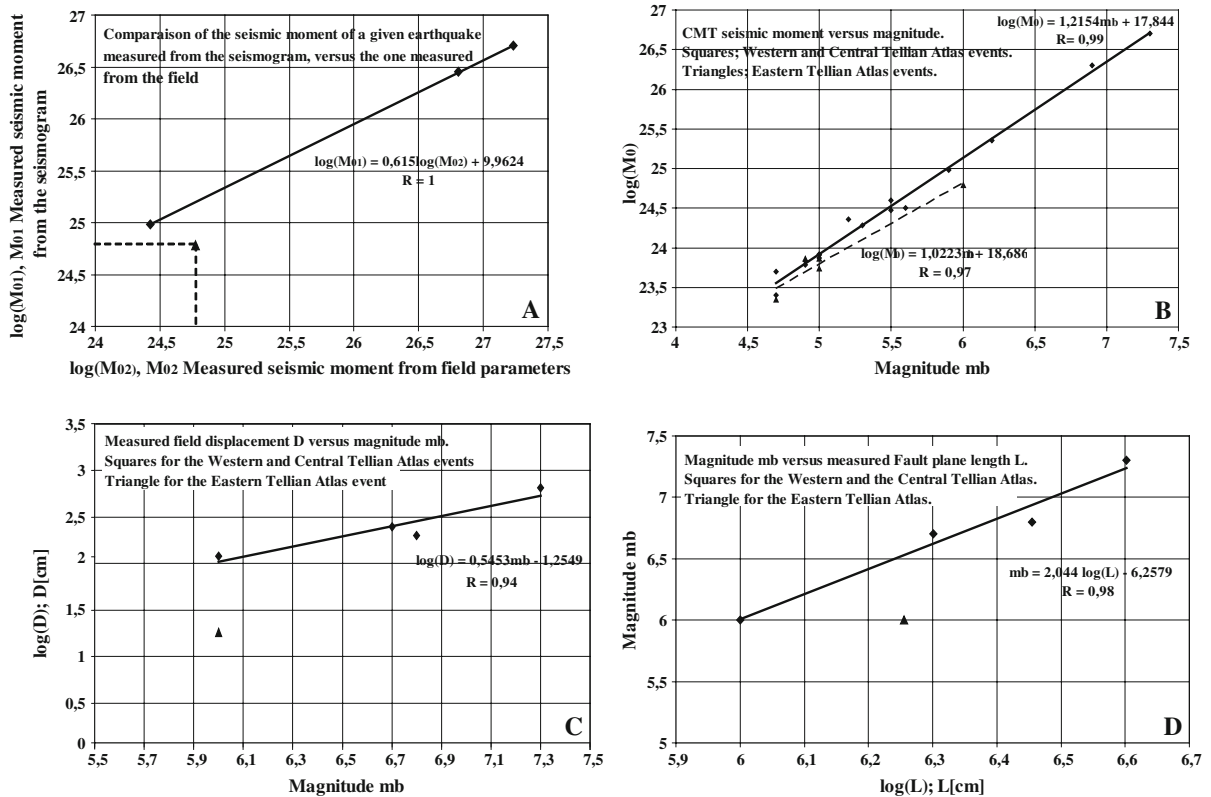


Figure 4

Earthquake source parameters versus magnitude. Squares represent events located in the western and central Tellian Atlas, whereas triangles are events located in the Eastern Tellian Atlas. (a) Measured seismic moment from data reported by the CMT Harvard catalogue, versus the seismic moment measured from field studies. Note that with the exception of the 1985 Constantine event most of the other western and central events have larger field seismic moments. (b) Measured seismic moments from seismograms versus magnitude for the Tellian Atlas. Note that both distributions are linear, with different slopes. (c) Measured field displacement versus magnitude. Note the linear trend of the Western and the Central Tellian Atlas events. (d) Magnitude versus measured fault plane length from field seismological mapping. Note the linear trend of the western and the central Tellian Atlas events

From the map of PHILIP and MEGHRAOUI (1983), the El-Asnam fault rupture is about 39 km long, and the aftershock spatial distribution fits well with the surface fault trace ruptures at  $\pm 3$  km. It is therefore justified and reasonable to consider the 1980 El-Asnam earthquake fault to be about 40 km long (MEGHRAOUI, 1982).

Thus the  $1.7 \times 10^{27}$  dynes-cm computed seismic moment from either the surface fault rupture and/or from the spatial aftershock distribution is more reliable than the one measured from the seismograms.

Indeed, the order of magnitude difference between the seismic moment determined from the seismograms and the one obtained from field data comes from the fact that the El-Asnam event is a complex source (DESCHAMPS *et al.*, 1982). In such a case, the computed seismic moment from P or S waves' source spectrum underestimates the source seismic moment (AKI, 1984). In fact, this observation holds for most earthquakes that occurred either in the western or the central Tellian Atlas (Fig. 4a), while it is not true for the only eastern Tellian event

(CONSTANTINE, 1985). The complex source of the Western and central Tellian Atlas events compared to the eastern ones is the reflection of the lateral variations in the regional main components of the stress tensor as well as of the differences in geodynamical and geological contexts of both regions.

### 5.2. 1980 El-Asnam Empirical Seismic Moment—Magnitude Relation

Equation 2 leads to the following expression of the seismic moment  $M_0$ :

$$\log(M_0) = 1.5 \log(A) + \log(\Delta\sigma) + \log(C'). \quad (13)$$

The empirical expression relating the seismic moment  $M_0$  to the magnitude  $m_b$  will be obtained from Eq. 13.

Using Eq. 3, which relates the fault plane area  $A$  to the magnitude  $m_b$ :

$$\log(A) = m_b + a. \quad (14)$$

From the 1980 El-Asnam parameters of Table 3, Eq. 14 becomes:

$$\log(A) = m_b + 5.61 \quad A[\text{cm}^2]. \quad (15)$$

The numerical value of the second term of Eq. 13,  $\log(\Delta\sigma)$ , is  $\log(54 \text{ bars})$  (Table 3).

Finally, the third term of Eq. 13 for the 1980 El-Asnam event,  $\log(C') \approx \log(1.18 \times (W/L)^{0.5}) \approx \log(0.84)$ .

Thus, the empirical seismic moment—magnitude relation (4) for the 1980 El-Asnam earthquake is:

$$\log(M_0) = 1.5m_b + 16.28 \quad M_0[\text{dynes-cm}]. \quad (16)$$

### 5.3. 1980 El-Asnam Empirical Displacement—Magnitude Relation

From Eq. 12:  $\mu D = M_0/A$ , and thus:

$$\log(D) = \log(M_0) - \log(A) - \log(\mu). \quad (17)$$

Replacing  $\log(M_0)$  by (16) and  $\log(A)$  by (15), Eq. 17 expresses Eq. 6 as:

$$\log(D) \approx 0.5m_b - 0.85 \quad D[\text{cm}]. \quad (18)$$

### 5.4. El-Asnam Empirical Fault Length—Magnitude Relation

The theoretical basis relating length  $L$  of the fault to the magnitude is taken from KANAMORI and ANDERSON (1975):

$$m_b = e \log(L) + f. \quad (19)$$

The value of constants  $e$  and  $f$  is estimated using the 1980 El-Asnam (MEGHRAOUI, 1988) and the 1954 Orleansville (BENOUEAR, 1994) surface rupture characteristics (Table 3). The reported length of the fault associated with the 1954 Orleansville earthquake and its displacement are consistent with the levelling data reported by BEZZEGHOUD et al. (1995).

$$e \approx 1.99,$$

$$f \approx -5.84.$$

Thus the Eq. 5 for the El-Asnam event is:

$$m_b \approx 1.99 \log(L) - 5.84 \quad L[\text{cm}]. \quad (20)$$

### 5.5. Empirical Relations for the Western and Central Tellian Atlas

The empirical relations obtained for the El-Asnam earthquake are used to determine the source parameters of the five western and central Tellian Atlas earthquakes listed in Table 3.

Using the flow chart described in Table 4, an overall consistency is obtained between the calculated source parameters from the empirical relations and the measured source parameters (Table 3) such as the 1989 Tipaza earthquake and the 2003 Boumerdes earthquake, both of which occurred in the western Tellian Atlas.

### 5.6. Empirical Relations for the Eastern Tellian Atlas

The measured seismic moments from seismic waves reported by the Harvard CMT catalogues (Table 1) are plotted against their magnitudes for the three Tellian Atlas blocks. The statistical trend for the eastern Tellian Atlas presents fundamental differences with both the central and western parts. Those

differences are statistically meaningful as shown on Fig. 4b, and cannot be explained by the inaccuracy of the seismic moment determination but rather by the fundamental change of the geodynamical context of the eastern Tellian Atlas compared to the central and western parts. The empirical relations that stand for quantifying the physical deformation in the central and the western Tellian Atlas collapse when applied to the eastern part because the rock physical properties in the eastern part change drastically. Indeed, the plateau disappears in the eastern part and is replaced by the spread of autochthonous old rocks corresponding to the intracontinental Saharan Atlas thrust belt that is considerably less active than the Tellian Atlas. The stress regime and the strike-slip faulting deformation in the eastern part contrast strongly with the thrust faulting seismic events and the compressive stress regime oriented NNW-SSE in the western part (MEGHRAOUI, 1988) (see Fig. 1; Tables 1, 3). Other data that give further substance to those fundamental lateral geological property variations of rocks as well as their geodynamical context are the representation of the measured field displacements versus magnitude as well as the measured field fault length versus magnitude (Fig. 4c, d). These figures show fundamental differences in rock response, depending upon whether the earthquake was located in the eastern Tellian Atlas or in the western and central parts. There was no earthquake in the eastern Tellian Atlas for which a field study has been carried out, except the 1985 Constantine event (BOUNIF *et al.*, 1987). The parameters of Table 3 relative to the Constantine event lead to the following empirical relations.

$$\log(A) = m_b + 6.25 \quad A [\text{cm}^2], \quad (21)$$

$$\log(M_0) = 1.02m_b + 18.69 \quad M_0 [\text{dynes-cm}], \quad (22)$$

$$\log(D) \approx 0.02m_b + 0.92 \quad D[\text{cm}], \quad (23)$$

$$m_b \approx \log(L) - 0.074 \quad L[\text{cm}]. \quad (24)$$

Equation 24 has been determined assuming that the seismicity in the eastern Tellian Atlas works mostly in strike-slip faulting and the seismicity depth is assumed to be about 15 km (Table 3).

Other useful empirical relations for the Tellian Atlas reported in the literature are presented in the Appendix.

### 5.7. Error Bars on the Empirical Relation Constants

The error bars on the computed constants of the empirical Eqs. 15, 16, 18 and 20 relative to the western and the central Tellian Atlas may be quantified by comparing those constants to the ones obtained from a linear least-squares regression of the overall western and central data of Table 3 (Fig. 4b–d), leading to the uncertainties given in Table 5. The error bars associated which some of the constants for the eastern part cannot be determined because no post-seismic field measurements have been conducted other than the reasonably good data of the 1985 Constantine earthquake (BOUNIF *et al.*, 1987).

## 6. Determination and Regionalisation of $Mag_{max}$ and $\dot{M}_\Sigma$

The empirical relations show the existence of two different tectonic regions with different mechanical

Table 5

Summary of the established empirical relations, relating magnitude to source parameters, for the Western, Central and Eastern Tellian Atlas. The determined constants are presented with their corresponding error bar

Empirical relations	Error bar on the determined empirical cstes for the Western Tellian Atlas	Error bar on the determined cstes for the Eastern Tellian Atlas
$\log(M_0) = cm_b + d$ [dynes-cm]	$c = 1.5 \pm 0.29$ ; $d = 16.28 \pm 1.56$	$c = 1.02 \pm 0.04$ ; $d = 18.69 \pm 0.27$
$\log(A) = m_b + b$ [cm <sup>2</sup> ]	$b = 5.61 \pm 2.53$	$b = 6.25 \pm ?$
$\log(D) = a_0m_b + b_0$ [cm]	$a_0 = 0.5 \pm 0.04$ ; $b_0 = -0.85 \pm 0.4$	$a_0 = 0.02 \pm ?$ ; $b_0 = 0.92 \pm ?$
$m_b = a_1\log(L) + b_1$ L in [cm]	$a_1 = 1.99 \pm 0.05$ ; $b_1 = -5.84 \pm 0.4$	$a_1 = 1.0 \pm ?$ ; $b_1 = -0.074 \pm ?$



responses: (1) the central and western Tellian Atlas, and (2) the eastern Tellian Atlas.

### 6.1. Maximum Magnitude in the Central and Western Tellian Atlas

The maximum Quaternary fault length in Central Algeria (MEGHRAOUI, 1988) is of the order of 65 km, and therefore exceeds the general maximal fault length in the western Tellian Atlas, i.e., about 40 km. The long western lineament extending from Mascara to El-Asnam has not been ruptured by a single earthquake but by a series of events in relay, which have globally migrated from west to east (MEGHRAOUI, 1988), whereas it is very likely that the central Tellian Atlas faults have been ruptured by single *en echelon* earthquakes, except perhaps for the Sahel fault. Thus, the maximal magnitude in the central Tellian Atlas is expected to be larger than in the western part. This statement is consistent with the following arguments:

- (a) The width of the High Plateau decreases dramatically (Fig. 1) and bends under the forces triggered by the convergence of the African plate toward Eurasia. That explains the difference in fault lengths and style of faulting between the western and the central parts and why much larger earthquakes could occur in the central Tellian Atlas.
- (b) In the western Tellian Atlas historical seismicity, to the contrary of the central part, there is no record of earthquakes that caused wide sea flooding and killed over 20,000 people (AMBRASEYS, 1983; MOKRANE *et al.*, 1994). This supports the fact that the largest earthquake in the Algiers region is considerably larger than 7.3, the largest earthquake ever recorded in the western Tellian Atlas. Using Eq. 20 and the maximum fault length from Meghraoui's map, about 65 km, the largest magnitude in central Algeria is found to be about 7.7.
- (c) With a 7.7 maximal magnitude, from Eq. 16 the maximum seismic moment in the central Tellian Atlas,  $M_{0 \max}$ , has a value of  $6.76 \times 10^{27}$  dynes-cm. The seismic moment rate  $\dot{M}_{\Sigma}$  of the central Tellian Atlas is of the order of  $3.92 \times 10^{25}$  dynes-cm-year<sup>-1</sup> (see below).  $\beta$ , a coefficient characterizing the seismicity of the region (MOLNAR, 1979), is of the order of 0.54,

calculated from Eq. 16 and using the coefficients  $a'$  and  $b'$  in Gutenberg relation (7) given by BENOUAR (1994) for the Tellian Atlas (Appendix). From Eq. 9, the time necessary to nucleate an earthquake of such seismic moment is of the order of 375 years, which is consistent with the 351 years time span separating the two largest earthquakes in the central Tellian Atlas, between the 1365 and the 1716 events (AMBRASEYS, 1983).

Thus, while the empirical relations did not permit differentiation between the central and western Tellian blocks, their maximum magnitude is different, respectively 7.7 and 7.3.

### 6.2. Gaps and Magnitudes

In the following parts, a gap is defined as the amount of time following a major earthquake during which no earthquake of magnitude larger than 5.2 has occurred.

In the western and central Tellian Atlas, using data spanning the time period from 1716 to present, a plot of magnitude versus gap duration after major earthquakes ( $\text{Mag} \geq 6.4$ ) shows a clear statistically linear trend, with a correlation coefficient  $R \approx 0.92$  (Fig. 5a). This plot will be used either (1) to estimate a gap duration after a major earthquake of known magnitude, or (2) to estimate the unknown magnitude of a major historical earthquake from the duration of the gap following it. Using the latter, the magnitude of the 1716 (19-year gap) earthquake is determined as 7.7.

In the western Tellian Atlas, using data from 1790 to present, another clear linear trend is obtained when plotting magnitude versus gap duration before major earthquakes, with a correlation coefficient  $R \approx 0.95$  (Fig. 5b). This pattern will be used to estimate the magnitude of pending major earthquakes. Thus, between the 1673 and 1716 events there is a 43-year gap, which corresponds to a pending magnitude 7.7 earthquake, as also found by other means for the 1716 earthquake.

### 6.3. Seismic Moment Rate $\dot{M}_{\Sigma}$ in the Central and Western Tellian Atlas

To show that the seismic moment rate of the central and western Tellian Atlas is about the same,

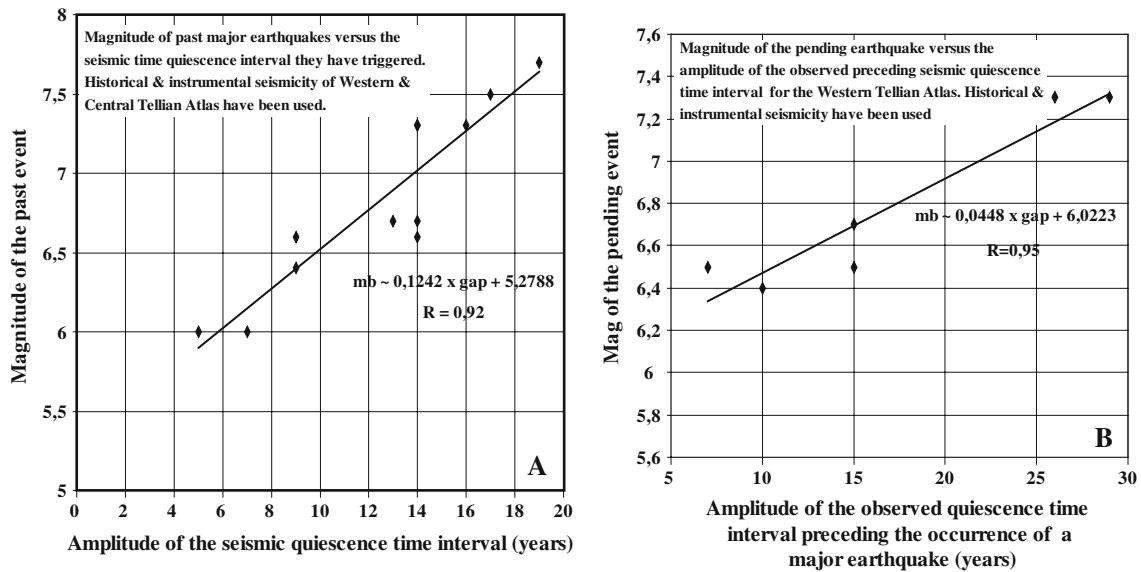


Figure 5

(a) Magnitude versus following seismic quiescence duration for the western and central Tellian Atlas. Time quiescence is defined as the time interval following a major earthquake during which no magnitudes  $\geq 5.2$  earthquakes have occurred. Note the formidable linear trend of the distribution (coefficient of correlation 0.92). This graph is used to determine the unknown magnitude of a past historical earthquake on the basis of the quiescence that follows. (b) Magnitude of pending earthquake versus preceding observed duration of seismic quiescence for the western Tellian Atlas events. Note the formidable linearity ( $R \approx 0.95$ ). This graph allows estimation of the pending earthquake magnitude with a reasonable accuracy of  $\pm 0.3$

a recent compilation of the seismicity from different catalogues from 1910 to 2007 is used (see section Data and Methodology, and Table 2). During this period, three events with a magnitude larger or equal to 6.0 have occurred in the central Tellian Atlas. Summing the seismic moments of all events with a magnitude larger or equal to 4.7 and less than 6.0 results in showing that all these events are equivalent to 3.5 magnitude 6.0 events. It follows that 6.5 events occurred in the central Tellian Atlas during the time period 1910–2007 with seismic moments larger or equal to  $1.9 \times 10^{25}$  dynes-cm (the seismic moment corresponding to a magnitude 6.0 event).

According to MOLNAR (1979), the number of events,  $N(M_0)$ , with seismic moments larger or equal to  $M_0$  that occurred during a time  $\Delta t$  is given by:

$$N(M_0) = \frac{1}{T(M_0)} = \frac{(1 - \beta) \dot{M}_\Sigma}{M_0^\beta M_{0\max}^{(1-\beta)}}, \quad (25)$$

where  $M_{0\max}$  is the maximal seismic moment that can occur in the considered region.

Taking  $N(M_0)$  for the Central Tellian Atlas during the period 1910–2007 as the ratio  $6.5/(93 \text{ years})$ ,  $M_{0\max}$  corresponding to a maximum magnitude of 7.7,  $M_0$  corresponding to a magnitude 6 event, and the  $\beta = 0.54$  value calculated above,  $\dot{M}_\Sigma = 4.3 \times 10^{25}$  dynes-cm/year.

The same formula applied to the western seismicity covering the 1790—present time period leads to  $\dot{M}_\Sigma = 3.92 \times 10^{25}$  dynes-cm-year $^{-1}$  for the western Tellian Atlas, consistent with the value deduced from the work of LAMMALI et al. (1997).

$\dot{M}_\Sigma$  values for the central and western Tellian Atlas are very similar. Therefore, given both the limited time scale used for estimating  $\dot{M}_\Sigma$  and the uncertainties of the seismicity in the central part, the western seismic moment rate will be used for both the central and western parts.

Thus, even though much larger earthquakes have occurred in the central Tellian Atlas than in the western part, both regions have about the same seismic moment rate and the same thrust faulting mechanism of deformation.



#### 6.4. Maximum Magnitude and Seismic Moment Rate $\dot{M}_\Sigma$ in the Eastern Tellian Atlas

From the maximum fault length of 62.8 km mapped in the eastern Tellian Atlas by MEGHRAOUI (1988), the maximum magnitude, given by (24), is of the order of 6.7.

$\dot{M}_\Sigma$  is computed the same way as for the central and western Tellian Atlas, using BOUGHACHA (2003) seismicity catalog from 1716 to 2000, in which are reported eight earthquakes with magnitudes larger than or equal to 5.5, from November 1869 to December 2000. A value of 0.06058793 is found for  $N(M_0)$ . From Eq. 22, the maximum seismic moment  $M_{0 \max}$  for the eastern Tellian Atlas has a value of  $3.34 \times 10^{25}$  dynes-cm (Mag  $\approx$  6.7) and from (25),  $\dot{M}_\Sigma$  for the eastern Tellian Atlas is found to be  $1.14 \times 10^{24}$  dynes-cm-year<sup>-1</sup>, an order of magnitude lower than for the western and central Tellian Atlas.

An alternate way to determine  $\dot{M}_\Sigma$  is to use the 39 year time interval of magnitude 6.0 earthquakes extracted from Table 2:

Aug. 1908	$I_0 = \text{VIII}$	North of Constantine
Aug. 1947	$I_0 = \text{VIII}$	Oued Hamimim
Oct. 1985	$I_0 = \text{VIII}$	El-Haria

Using this time interval, the eastern Tellian Atlas  $\beta$  of 0.83 (see Appendix), together with relations (22) and (9), lead to  $\dot{M}_\Sigma = 1.3 \times 10^{24}$  dynes-cm/year, very similar to the previous value. However, the first value will be considered as the  $\dot{M}_\Sigma$  for the eastern Tellian Atlas because it is based on a considerably larger seismicity time scale.

#### 7. Determination and Regionalisation of $\text{Sum}_D(t)$ , $\text{Sum}_{M_0}(t)$ , and $V(t)$

The collision of the African plate with the Eurasian plate is accommodated in the Tellian Atlas by displacements along faults with different deformation mechanisms. Equations 18 and 23 are used to associate displacement for each earthquake according to its magnitude, from which we obtain the cumulative displacements versus time  $\text{Sum}_D(t)$  absorbed by the

faults generated in each block of the Tellian Atlas (Fig. 6). Given the Tellian Atlas tectonic context,  $\text{Sum}_D(t)$  slope does not represent the plate convergence velocity. It certainly represents, however, for a given region, a meaningful number for earthquake prediction and prevention. As will be shown later  $\text{sum}_D(t)$  (Fig. 6) could serve as one of the practical bases to assess the seismic threat in the Tellian Atlas with all its implications.

Similarly, the cumulative seismic moment versus time,  $\text{Sum}_{M_0}(t)$ , is obtained from Eqs. (18) and (23) (Fig. 9c).

Another useful computed parameter is the instantaneous velocity  $V(t_i)$  computed, in each block, for every event occurring at time  $t_i$  as follows:

$$V(t_i) = \frac{\text{Sum}_D(t_i)}{t_i - t_0} \quad [\text{cm/year}], \quad (26)$$

where  $t_0$  corresponds to an arbitrary point located on the linear slope on the graph of Fig. 6a.

#### 7.1. Western Tellian Atlas (Oran Region)

##### 7.1.1 Cumulative Displacement versus Time

The cumulative displacement versus time,  $\text{Sum}_D(t)$ , absorbed by the faults generated in the western Tellian Atlas is obtained using earthquakes with magnitudes larger or equal to 4.7 that have occurred from 1910 to 2007 (Fig. 6a). The seismicity associated with the western Tellian Atlas is far from being completely random, but follows an astonishing remarkable pattern (Fig. 6a). A linear trend is obtained by applying an optimal regression to the point distribution reflecting stress release through time. This pattern is consistent with the uniform NE–SW thrust faulting lineament limited by the rigid undeformed Plateau. The larger the displacement gap, the larger the probability of occurrence of a large earthquake. A gap is defined as the amount of time during which no earthquake of magnitude larger than 5.2 has occurred.

Thus, one could have known that around 1945 and 1972 the western Tellian Atlas started to be seismically threatening because of large displacement gaps that could nucleate an earthquake of magnitude greater or equal to 6.6 at anytime. Indeed, it

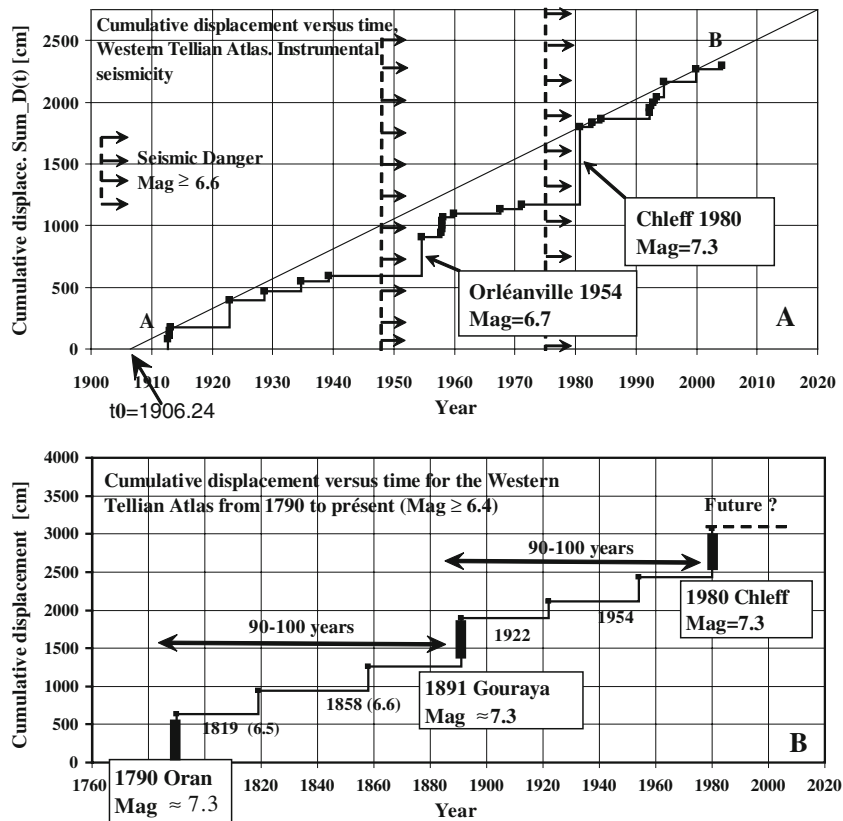


Figure 6

(a) Cumulative fault displacements versus time for the western Tellian Atlas. Only events with a magnitude larger or equal to 4.7 located in the Tellian Atlas, excluding the Rif events, are considered (see text). Aftershock sequences associated with the major events, such as the 1954 and 1980 earthquakes, are not considered. Note the straight regression line enveloping the sets of points. Note that the major destructive 1954 Orleansville and 1980 El-Asnam earthquakes could have been predicted in time before their occurrence around 1945 and 1972, respectively. (b) Observed cumulative displacement versus time for the western Tellian Atlas using instrumental and historical seismicity, considering only relatively large earthquakes with magnitude  $\geq 6.4$ . Magnitudes of the historical events are from Table 1. Note the formidable regularity of the displacements absorbed. The theoretical recurrence time intervals evaluated from Molnar formalism are consistent with these observations

culminated in both situations by the destructive 1954 Orleansville (mag = 6.7) and 1980 El-Asnam (Mag = 7.3) earthquakes. The 1954 earthquake did not completely release the accumulated stresses and explain why the 1980 earthquake was far more damaging and with a much larger magnitude (7.3). In situ stress measurements after the 1980 El-Asnam earthquake support the fact that most of the accumulated stresses have been completely released (BEGHOUL, 1984).

Our current knowledge of the historical seismicity of the western Tellian Atlas substantially confirms these results:

- the western Tellian Atlas historical seismicity from 1790 to present (see Table 2), considering events with magnitudes larger than 6.0, also shows major displacement gaps corresponding to a lack of relatively large magnitude earthquakes before the occurrence of major earthquakes (Fig. 6b). In-between the largest earthquakes (Mag = 7.3) two medium-sized earthquakes occurred, separated by an astonishing regular time interval (Fig. 6b). The 1891 Gouraya and the 1887 El-Kalâa events are both relatively large events (AYADI, 1996; MOKRANE *et al.*, 1994; BOUGHACHA, 2003), located less than 160 km apart, with an equivalent magnitude of

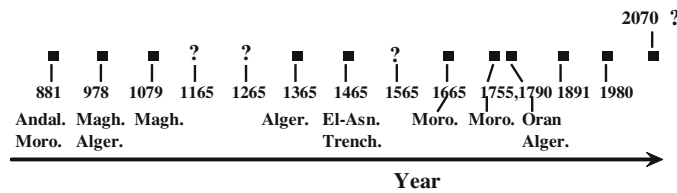


Figure 7

Western Tellian Atlas historical seismicity (881-present). Data from catalogues and trench investigations (see text). Note the astonishing regular occurrence earthquakes of magnitudes of the order of 7.3 every 89–100 years, consistent with the results from Molnar and Kostrov's formalisms. See text for magnitude estimations

about 7.3, comparable to the 1980 El-Asnam or the 1790 Oran earthquakes (LÓPEZ MARINAS and SALORD, 1990; BOUGHACHA, 2003).

- extending the western Tellian Atlas historical seismicity to 881 (Fig. 7) from POIRIER and TAHER (1980), Table 2 and trenches study (MEGHRAOUI, 1988; MEGHRAOUI and DOUMAZ 1996) show that a major earthquake occurs in this region about every 100 years. Thus, the time recurrence interval of major earthquake in the western Tellian Atlas, found previously, is also fulfilled up to the year 881. As the latest major event occurred in 1980 the next one will probably occur around the years 2070–2080, somewhere in the region extending from Meknes to western Algiers. Although the 1365 event is supposed to be located in the central Tellian Atlas, it has been included in the plot and is consistent with the historical seismicity that concerns the western Maghreb for the most part. The very large mislocation associated with historical events is well known and require better future documentation.

As since 1980 no magnitude  $\geq 6.4$  earthquake has occurred, there is a very high probability that a magnitude 6.4–6.7 earthquake will occur in the western Tellian Atlas. According to the patterns observed for the previous large earthquakes, the next magnitude 6.4–6.7 should occur around 2010–2015, while the next large event (Mag > 7) should occur around 2070–2080.

However, it is obviously not possible with these data to determine the location of the next earthquake, which could occur anywhere in the western Tellian Atlas. Further geological and geophysical

investigations, such as in situ stress and geodetic field data measurements, and/or microseismic activity monitoring, are required to determine better constraints on the event location.

### 7.1.2 Instantaneous Velocity

For the western Tellian Atlas  $t_0$  has been taken as year 1906.24. Before the occurrence of the 1954 and 1980 earthquakes a large velocity decrease is observed, followed by a large seismicity gap (Fig. 8). Thus, when an instantaneous velocity drop comes to an end and is followed by a seismicity gap, the region becomes under the threat of a magnitude  $\geq 6.0$  earthquake. The western Tellian Atlas is currently experiencing a seismicity decrease, and the next seismicity gap will be a strong indication of a pending magnitude  $\geq 6.0$  event, although according to Sum\_ $D(t)$ , not a magnitude >7.0 event.

## 7.2. Central Tellian Atlas (Algiers Region)

### 7.2.1 Cumulative Displacement versus Time

The cumulative displacement versus time, Sum\_ $D(t)$ , absorbed by the central Tellian Atlas faults using magnitudes  $\geq 4.9$  earthquakes, shows two remarkable patterns (Fig. 9a):

- a long-time scale regularity of about 100 years for magnitude  $\geq 6.6$  events (continuous line);
- a short-time scale regularity of about 50 years for magnitude  $\geq 6.0$  events (dashed lines).

*Long-time scale.* The long time scale is based on the 1910 magnitude 6.6 and 2003 magnitude 6.8

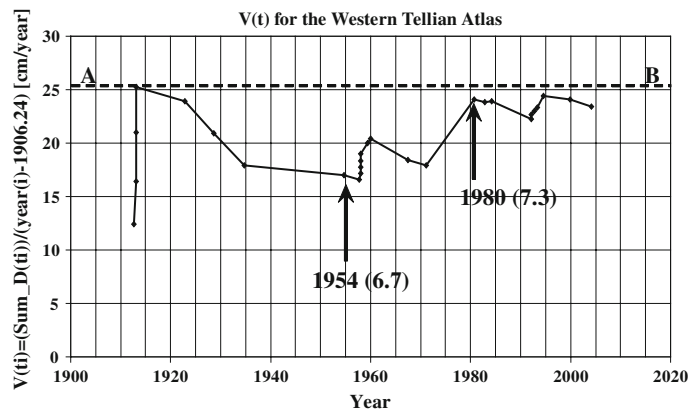


Figure 8

Computed velocity versus time for the western Tellian Atlas, according to Eq. 26. Note the similar pattern before the occurrence of the major 1954 and 1980 events

events. In fact, there has been a series of three successive magnitude 5.5, 5.5 and 5.6 earthquakes in the period 1959–1960, roughly equivalent to a single magnitude 6.0 earthquake, a magnitude deficit of 0.6 according to the long-term pattern. Some 43 years later (2003) occurred the destructive, magnitude 6.8, Boumerdes earthquake. Its magnitude was larger than 6.6 because the accumulated stresses have not been completely released in 1960. Considering seismic moments, the 0.6 difference in magnitude that has not been liberated in 1960 corresponds to about the 0.2 magnitude excess (6.6–6.8) of the 2003 event. Therefore, the seismicity of relatively large earthquakes in the central Tellian Atlas is far from being totally random.

In fact, preliminary results of an ongoing work using the central Tellian Atlas historical seismicity from 1716 to 1910 also show a regular occurrence of earthquakes of about 6.6 magnitudes (Fig. 9b). The great destructive 1716 and 1825 earthquakes must have been triggered by relatively large earthquakes (Mag: 6.4–6.6), because they fall into about the same astonishing 1910–2003 recurrence time interval (Fig. 9b). Magnitudes used to plot the historical cumulative displacement versus time,  $\text{Sum}_D(t)$  have been obtained in the following manner:

- as shown in a previous section, the destructive 1716 Algiers earthquake (AMBRASEYS, 1983), certainly the largest central region earthquake, has a magnitude of about 7.7;
- the 1772 and 1825 earthquakes are the only events for which no substantial information about its magnitude is available. The 1772 earthquake magnitude has been estimated at 6.2–6.4, given the 8-year seismicity gap following this event (Fig. 5a), based on the 1780 earthquake (BOUGHACHA, 2003). This is consistent with the approximately 50-year regular recurrence time interval of the other well documented earthquakes with similar magnitude (Fig. 9b).

Similarly, the 1825 Blida earthquake was most probably of a magnitude approaching 7.4, from the seismic 17-year gap duration that followed this event up to the 1842 earthquake (Fig. 5a). Moreover, using the empirical relation (16) relating magnitude to seismic moment, the seismic moment rate  $\dot{M}_\Sigma$  from 1716 to the present is compatible with 1825 event magnitude of about 7.4.

*Short time scale.* Contrastingly the western Tellian Atlas, stress accumulation in the central Tellian Atlas is released by double earthquakes (Fig. 9a). This is a good situation, as it prevents the release of the accumulated

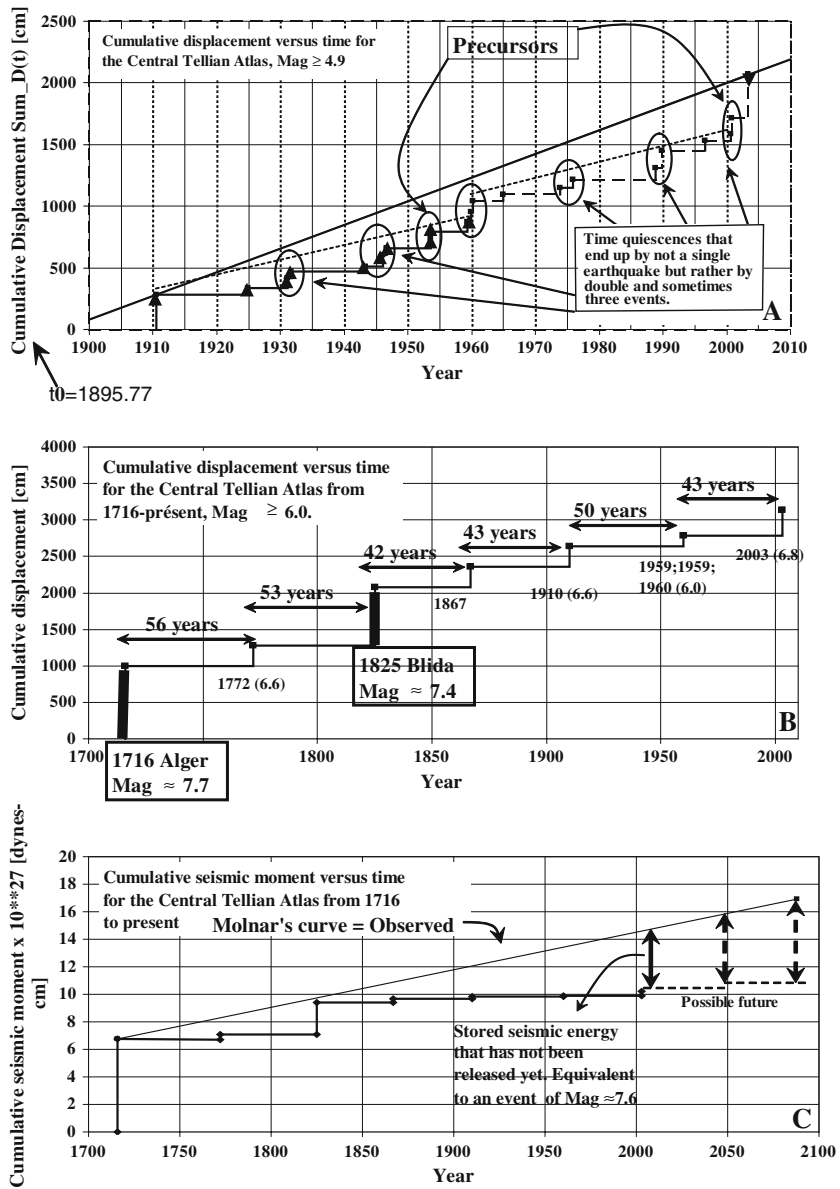


Figure 9

(a) Cumulative fault displacements versus time for the central Tellian Atlas, with magnitude  $\geq 4.9$  events. An interesting general observation is that without the occurrence of one or several smaller earthquakes before a relatively large event ( $\geq 6.0$ ), a resulting single earthquake would have had more catastrophic consequences. *Triangles* and *squares* correspondent to two distinct active tectonic features oriented NE–SW and NW–SE, respectively (b) Observed cumulative displacement versus time for the central Tellian Atlas, using instrumental and historical seismicity. Only earthquakes with magnitudes  $\geq 6.6$  are represented. The magnitudes of the historical events are the ones summarized in Table 1. Note the astonishing recurrence regularity of earthquakes of magnitude about 6.6 every 48 years. There is a very high probability that a massive earthquake will occur after the recent destructive 2003 Boumerdes earthquake. (c) Cumulative seismic moment versus time of magnitude  $> 6.0$  events in the central Tellian Atlas. Considerable seismic energy that has not been released yet, equivalent to a magnitude 7.6 earthquake

stresses by a single more damaging earthquake. For example, the 1989 magnitude 6.0 Tipaza earthquake was preceded by the 1988 magnitude 5.6 Oued Djir

earthquake. It is the case of most earthquakes in the Algiers region, certainly linked to the *en echelon* fault system of the Algiers region.

Locations of earthquakes corresponding to the time intervals 1910–1960 and 1960–2003 show that the two sets of earthquakes are distributed on distinct fault directions.

The 1910–1960 cloud of earthquakes oriented NW–SE is low-dip angle thrust fault events, located in-between the coastline and the margin of the High Plateau.

The 1960–2003 cloud of events oriented NE–SW is high-dip angle thrust fault earthquakes, located along both the coastline and the margin of the High Plateau. They have about the same direction as the major thrust reported on FABRE (1978) geological map (Fig. 2). Therefore, this central major structural feature currently appears to be seismically active.

### 7.2.2 Cumulative Seismic Moment versus Time

Based on the estimation of historical earthquake magnitudes obtained in the previous section, the cumulative seismic moment versus time,  $\text{Sum}_M(t)$ , is estimated from Eq. (16) (Fig. 9c). It clearly appears that despite the destructive 2003 magnitude 6.8 Boumerdes earthquake, a substantial amount of the seismic energy currently stored in the crust has not been released yet. Based on the linear trend obtained from the 1716 and 1825 events, the central Tellian Atlas may nucleate an earthquake with a magnitude as large as 7.6 (Fig. 9c).

### 7.2.3 Instantaneous Velocity

For the central Tellian Atlas  $t_0$  has been taken as year 1,895.77. There is a strong correlation—coefficient of correlation equal to 0.99—between the 1910–1960 and the 1960–2003 curve patterns (Fig. 10). It indicates that the nucleation of a series of three successive events (the 1959–1960 series) or a relatively large event such as the 2003 magnitude 6.8 Boumerdes earthquake have about the same evolution in time. In other words, when a velocity decrease is followed by almost no velocity variation, there is a great chance that a relatively large earthquake is imminent.

The derivative of the sum of displacement relative to time,  $\frac{\Delta \text{Sum}_D(t)}{\Delta t}$ , versus time shows large variations before the occurrence of the 1959 series of successive events (equivalent to a magnitude  $\approx 6.0$  event) or the relatively large 2003 earthquake (Mag  $\approx 6.8$ ) (Fig. 11). A very short time ( $<6$  years) before the occurrence of a relatively large earthquake (mag  $\geq 6.0$ ) two smaller events with magnitudes  $\geq 5$  occur, separated by a time interval of the order of 1.5–3 months. In other words, the time span between double earthquakes decreases dramatically before the occurrence of relatively large earthquakes. In fact, occurrence of double earthquakes closely separated in time before a relatively large earthquake is also well documented in the historical seismicity from 1867 to 1910 (Table 6).

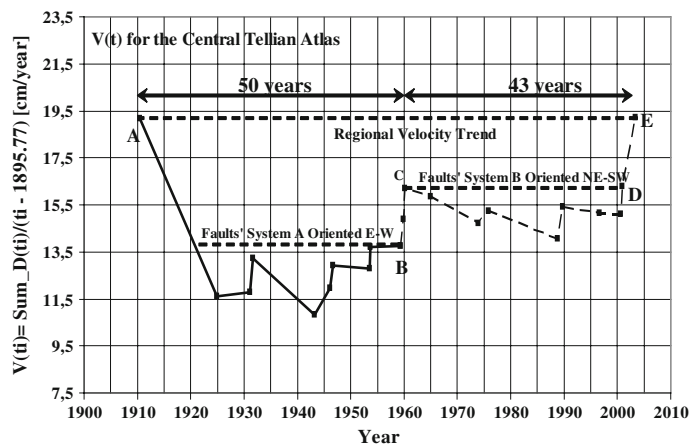


Figure 10  
 Computed velocity versus time, according to Eq. 26, for the central Tellian Atlas. The two curves describing the NE–SW and NW–SE fault systems; both having about similar patterns with a coefficient of correlation of 0.99

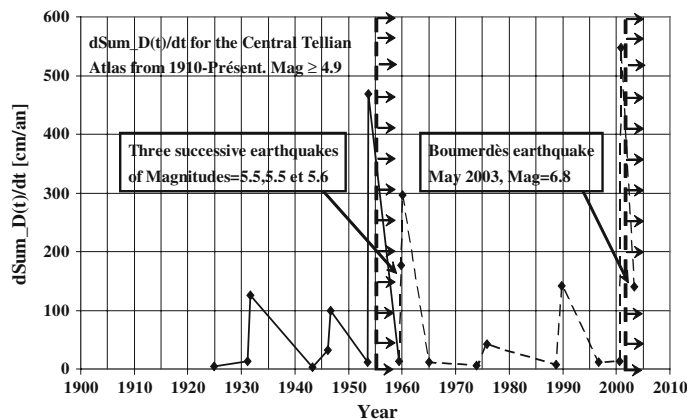


Figure 11

Derivative of the cumulative displacement versus time for the central Tellian Atlas. Note that the derivative is large before the occurrence of successive earthquakes or of a large earthquake, such as the May 2003 Boumerdes event. The two curves describing the NE–SW and NW–SE distinct active tectonic features

Table 6

List of earthquakes (Mag  $\geq 6.0$ ) that have occurred in the Central Tellian Atlas and that have been preceded by small double earthquakes

Timing & location of relatively large earthquakes located in the central Tellian Atlas (Mag  $\geq 6.0$ ) The precursors in terms of small double earthquakes (Mags  $\geq 5.0$ ) closely separated in time (<10 months); occurring a short time (<6 years) before a relatively large earthquake (Mag  $\geq 6.0$ )

Jan. 2nd 1867; Lat = 36.42, Long = 2.68 Mag $\approx 6.6?$ (see text)	Jan 16th 1865; Lat = 36.50, Long = 3.10; Mag = 3.8 (1) ?
June 24th 1910; Lat = 36.30, Long = 3.70 Mag $\approx 6.6$ (1), 5.7–6.6 (2), 6.7 (5)	Feb 25th 1865; Lat = 36.75, Long = 5.08; Mag = 4.7 (1)?, 5.7 (2) ?
Feb. 21st 1960; Lat = 36.12, Long = 4.51	Jan 02nd 1909; Lat = 36.50, Long = 2.90; Mag ?
May 24th 1959; Lat = 36.38, Long = 2.55	Oct 29th 1909; Lat = 36.70, Long = 3.10; Mag ?
Nov. 7th 1959; Lat = 36.00, Long = 4.10 Mags = 5.5; 5.5; 5.6	Jul 05th 1953; Lat = 36.20, Long = 3.5; Mag = 5.5 (3), 5.7 (2), 4.6 (1)
May 21st 2003; Lat = 36.98, Long = 3.66 Mag = 6.8	Aug 29th 1953; Lat = 35.80, Long = 5.00; Mag = 5.2 (3), 5.2–6.5 (2), 5.2 (1)
	Aug 18th 2000; Lat = 36.189, Long = 4.955; Mag = 5.2
	Nov 10th 2000; Lat = 36.550, Long = 4.77; Mag = 5.9

(1) BENOUAR 1994; (2) MOKRANE et al. 1994; (3) BOUGHACHA, 2004; (4) AYADI 1996; (5) BEZZEGHOUD et al. 1996

To the contrary of what is observed in the western Tellian Atlas, the instantaneous velocity gives no clue about the pending occurrence of a major earthquake (mag  $\geq 7$ ). It is only an indication of the occurrence of relatively large events (mag  $\geq 6.0$ ).

### 7.3. Eastern Tellian Atlas (Constantine-Tunis Region)

#### 7.3.1 Cumulative Seismic Moment versus Time

Because of the very small displacements accommodated by the faults of the eastern Tellian Atlas, both the sum of the displacement versus time,  $\text{Sum}_D(t)$  and the instantaneous velocity versus time  $V(t)$ , present

less usefulness than the graph of the cumulated seismic moment versus time  $\text{Sum}_{M_0}(t)$  (Fig. 12).

In the eastern Tellian Atlas, a gap is defined as the amount of time following a major earthquake during which no earthquake of magnitude larger than 5.6 has occurred, as opposed to 5.2 in the western and central Tellian Atlas. The larger the gap (>80 years, mag  $\leq 5.6$ ), the larger the probability that an earthquake with a magnitude 6.7 is to occur (Fig. 12).

## 8. Application of Molnar Formalism

The great advantage of Molnar formalism (1979), Eq. 9, is that (1) it may be used independently of the



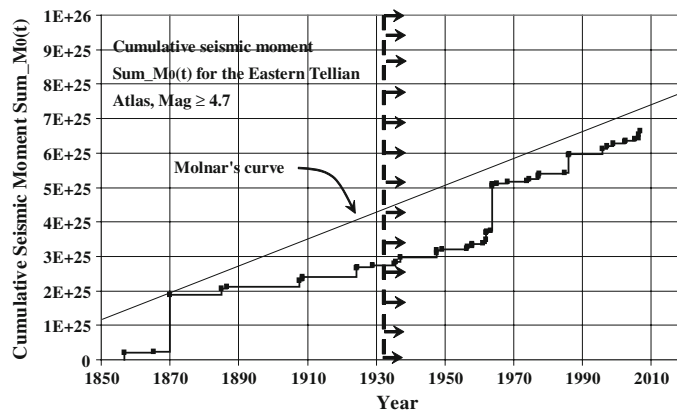


Figure 12

Cumulative seismic moment versus time along the faults of the eastern Tellian Atlas. Only events with magnitude  $\geq 4.7$  are considered (*filled squares*). Note that the 80–100 year time recurrence of a magnitude 6.3–6.5 earthquakes predicted using observations is consistent with the recurrence from the Molnar formalism. The *vertical dashed line* indicates the timing when the region could nucleate an earthquake of magnitude 6.2

tectonic context of the region, and (2) it allows the prediction of recurring events in all ranges of magnitude events. This is particularly useful for Maghreb, where the Agadir event, of magnitude 5.7 only, claimed over 12,000 lives, substantially more than the 3,000 people killed during the El-Asnam earthquake, with a much larger magnitude (7.3).

The error bar on the computed recurrence time interval is of the order of  $\pm 12.7\%$  when the equivalent magnitudes of  $M_0$  and  $M_{0 \max}$  are known at  $\pm 0.1$ .

### 8.1. Western Tellian Atlas

As has been shown for the western and the central Tellian Atlas,  $\beta = 0.54$  and  $M_{0 \max} = M_{0 \text{ El-Asnam1980}} = 1.74 \times 10^{27}$  dynes-cm (Table 3).

From Eq. 9 the time  $T(M_0)$  necessary to nucleate a magnitude  $\geq 7.0$  event, similar to the 1980 El-Asnam earthquake, is evaluated to about 97 years  $\pm 12$  years i.e., 85–109 years, which implies that the next major event should occur around the years 2065–2089; the exact observed occurrence (2070–2080) deduced from the empirical relations (Fig. 6).

Interestingly, using Kostrov formalism, Eq. 11, with  $\dot{M}_\Sigma = 3.92 \times 10^{25}$  dynes-cm-year $^{-1}$ ; the crust rigidity coefficient  $\mu = 3.3 \times 10^{11}$  dynes-cm $^{-2}$ ; the 1980 El-Asnam fault plane surface area  $A = 8 \times 10^7$

cm $^2$  (Table 3), and the plate average convergence rate  $\bar{V} = D_{\max}/\Delta t$  ( $D_{\max} \approx 6.6$  m, Table 3), lead to a time recurrence interval  $\Delta t$  for El-Asnam events of the order of 89 years, consistent with the results from both Molnar formalism and the empirical relations.

### 8.2. Central Tellian Atlas

From Eq. 9 the time  $T(M_0)$  necessary to nucleate a magnitude  $\geq 6.6$  relatively large earthquake, similar to the 1910 event, is found to be about 48 years, exactly the observed time recurrence obtained from the empirical relations (Fig. 9).

With the same equation, it is also shown that the next large earthquake of approximate magnitude 7.7, such as the 1716 Algiers event, will occur around the year 2091.

The cumulative seismic moment versus time obtained from Molnar formalism clearly shows that a large earthquake (mag  $\geq 7.6$ ) is soon to occur either around 2050 or 2091, with a magnitude 7.4 or 7.7 respectively (Fig. 9c).

### 8.3. Eastern Tellian Atlas

The 1869 magnitude 6.4 earthquake occurred 94 years before the 1963 magnitude 6.3 event, a recurrence interval consistent with Molnar time



predictable formalism (9). Therefore, the seismicity of the eastern Tellian Atlas, as in the western and the central parts, is working with an astonishing regularity.

A summary of the time recurrence intervals calculated with Molnar formalism necessary to nucleate an earthquake of a given magnitude enlightens the different behavior of the three Tellian Atlas blocks together with their maximal magnitudes (Fig. 13). Furthermore, if one considers the spatial distribution of the seismicity in the Tellian Atlas, one notes that the earthquakes of magnitude larger or equal to 4.7 of the eastern part lie on a surface three times and 4.5 times larger than in the central and the western parts, respectively. Therefore, if one assumes that the depth of the seismicity is about the same from west to east, a reasonable assumption consistent with the ISC data from 1964 to the present; the volume of crustal rocks that are under brittle faulting in the eastern part is 4.5 larger than in the western part. It follows from Kostrov's Eq. 10 and utilizing the fact that the seismic moment rate in the eastern part of the Tellian Atlas is ten times lower; one can write the following equation:

$$\dot{\epsilon}_{\text{East}} = (\dot{\epsilon}_{\text{West}})/45. \quad (27)$$

This assumes the same crustal rigidity coefficient  $\mu$  for the rocks of both regions. This rough evaluation

is consistent with the observational slopes of the straight lines of Fig. 12 and its equivalent for the western part of the Tellian Atlas. Indeed, those graphs are in a way a certain representation of the strain rate of the considered regions. The ratio of those slopes between the western and the eastern parts is about 50, consistent with the rough but meaningful evaluation of the strain rates obtained from Eq. 27 using the observed seismicity and Kostrov's formula (10). Although the African plate converges faster at a rate of 2.8 cm/year toward Eurasia in the eastern part at the Gulf of Tunis compared to 0.5 cm/year at Gibraltar, the strain rate in the eastern part is 45 times lower because there is no condition of "blocage" (a state of strong interplate struggling). This is further amplified by the fact that the width of the rigid undeformed High Plateau is considerably reduced further east. Indeed, with no rigid High Plateau the seismicity becomes diffuse, and therefore the strain rate decreases dramatically. This explains why the eastern Tellian Atlas is by far less seismically hazardous than the western part.

## 9. Conclusion

The Africa-Eurasia convergence is not absorbed uniformly along the Tellian Atlas. In the western part

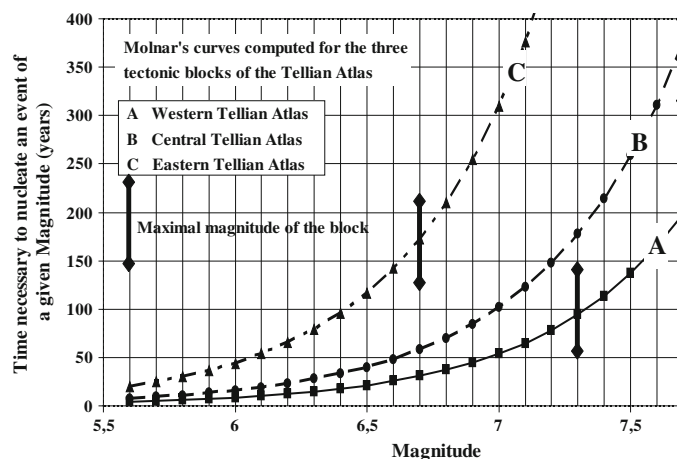


Figure 13

Evaluated time interval necessary to nucleate an earthquake of a given magnitude using Molnar's formalism, in the western (solid line, filled squares), Central (dashed line, filled circles) and Eastern (dotted dashed line, filled triangles) Tellian Atlas. Thick vertical bars indicate the maximal magnitude that could occur in each region. The largest earthquake is of an approximate magnitude 7.3 occurring about every 90 years in the western part; of 7.6–7.7 magnitude; every 300–375 years in the central part; of magnitude 6.7 every 170 years in the less seismic-prone eastern part. The error bar made on time evaluations is about 12.7%, assuming that the magnitudes are known at  $\pm 0.1$ .

it is accommodated by a set of NE–SW linear lineaments limited to the south by the thick rigid undeformed High Plains. In the eastern part, where no Plateau exists, the convergence is absorbed by a broad region of E–W strike slip faults. The central part is characterized by an intermediate context between the western and eastern parts, lying at the termination of the High Plateau, where the convergence is absorbed by a set of *en echelon* thrust faults.

Using parameters of the major earthquakes that have occurred in the Tellian Atlas for the past half century, empirical relations have been established, for the western (Oran and El-Asnam region), central (Algiers region), and eastern Tellian Atlas (Constantine-Tunis region), which relate earthquake magnitude to source parameters (fault plane area, length of the fault, displacement along the fault, and seismic moment). The same empirical relations are found for the central and western parts, while they are different for the eastern part.

These empirical relations are applied to the 1716–to present seismicity to obtain the cumulated displacements versus time,  $\text{Sum}_D(t)$ , and cumulated seismic moment versus time,  $\text{Sum}_{M_0}(t)$ . Together with various other geological and seismotectonic informations  $\text{Sum}_D(t)$  and  $\text{Sum}_{M_0}(t)$  show that the three different Tellian Atlas blocks are acting as distinct seismically decoupled seismotectonic regions.

In the western Tellian Atlas, including the region of El-Asnam (Orléansville, Chleff), the largest earthquake, with a magnitude of the order of 7.3, occurs about every 90–100 years along a fault system extending from El-Attaf to Meknes in Morocco. Both our current knowledge of the Tellian Atlas historical seismicity from the year 881 to present and theoretical calculations using Molnar and Kostrov formalisms support these statements.

Cumulative displacements versus time,  $\text{Sum}_D(t)$ , spanning the time period from 1790 to present, allow discernment of a clear relationship between events with magnitude  $\geq 6.0$  and activity gaps either preceding or following these events. Thus, both the 1954 and 1980 destructive earthquakes could have been predicted in time a few years before their occurrence. It also allows the determination that the western Tellian Atlas is currently under the threat of a

relatively large event ( $\text{mag} \leq 6.7$ ) that should occur by 2015.

According to Molnar formalism, the central Tellian Atlas, including the region of Algiers, the largest earthquake with magnitude of the order of 7.7, occurs about every 375 years. This is consistent with the observations of  $\text{Sum}_D(t)$  based on the empirical relations. As for the western part, the sum of the displacement versus time,  $\text{Sum}_D(t)$ , absorbed by the central faults system manifests a significant regularity from 1716 to present. It is demonstrated theoretically as well as observationally that a magnitude 6.6 earthquake occurs every 48 years. These relatively large earthquakes have triggered the large 1716 and 1825 destructive earthquakes ( $7.7 \geq \text{Mag} \geq 7.4$ ). Therefore, the 2003 magnitude 6.8 Boumerdes earthquake might be a precursor for an enormously catastrophic earthquake that should occur around 2050 or 2091, with a magnitude 7.4 or 7.7, respectively (Fig. 9c). In this zone precursors other than gaps have been observed on a long-time scale involving high  $\frac{\Delta \text{Sum}_D(t)}{\Delta t}$ , before the occurrence of relatively large earthquakes ( $\text{mag} \leq 6.8$ ) (Table 6). This was the case for the recent destructive 2003 Boumerdes earthquake that could have been predicted in time three years before its occurrence.

The same observations have been established for the eastern Tellian Atlas using the historical seismicity from 1839 to present. The largest magnitude is of the order of 6.7 compared to 7.3 and 7.7 for the western and the central Tellian Atlas, respectively. This may be explained by the condition of ‘non-blocage’ existing between the African and Eurasian plates in the eastern Tellian Atlas near the Gulf of Tunis, reflected by a strain rate 45 times lower than in the western part (27). The cumulative displacement versus time,  $\text{Sum}_D(t)$ , shows the occurrence of a magnitude of about 6.4 every 95 years. This observed time recurrence period is consistent with the theoretical evaluation from Molnar formalism. The results for the eastern Tellian Atlas reveal that it is far less seismically hazardous than the two other parts.

Table 7 summarizes most of those important seismic parameters for each Tellian Atlas tectonic block, and describes their corresponding pattern when the seismic risk in each block becomes hazardous. Table 8 presents a summary of all important

Table 7

*Regions with their corresponding seismic parameters when the situation is at very high seismic*

Regions	Sum_ $D(t)$	Derivative of the displac.	Computed Displacem. Velocity $V(t_i)$ at time $t_i$ . It is not a plate's velocity (see text) significant decrease of $V(t)$ before any major earthquake ( $\text{Mag} \geq 6.7$ ).	Observations
Western Tellian Atlas	Gap in displacements before major earthquakes ( $\text{Mag} \geq 6.7$ ). Gap $\geq 50$ years ( $\text{Mag} \leq 4.9$ ) (see Fig. 6)		$V(t_i) \leq 17.5$ cm/year	Gap and velocity both have to be fulfilled
Central Tellian Atlas	No Gap but regular recurrence time interval (see Figs. 9b and 13)	This value is large before any major earthquake ( $\text{Mag} \geq 6.7$ ). $\geq 4$ m/year	$V(t_i) \leq 15.5$ cm/year	No variation in velocity followed by a velocity exceeding 0.15 m/year could be followed either by a series of events or by a large earthquake. All parameters have to be fulfilled
Eastern Tellian Atlas	Gap in displacements before major earthquakes ( $\text{Mag} \geq 6.7$ ). Gap $\geq 80$ years ( $\text{Mag} \leq 5.6$ ) (see Fig. 12)		$V(t_i) \leq 0.25$ cm/year	Large gap with no variation in velocity corresponds to a relatively dangerous seismic situation

observational and measured physical parameters of the Tellian Atlas, strongly needed in any seismological, geophysical, geodynamical or civil engineering modelling.

#### *Acknowledgments*

We would like to thank M. Barazangi of Cornell University, Ithaca, New York, USA and an anonymous reviewer who have read our manuscript and brought extremely helpful and useful suggestions that have contributed to significantly enhance the overall structure of this work. We would like to thank Mustapha Meghraoui of IPGP of Strasbourg, France for having very carefully read our manuscript and having brought useful and helpful suggestions. I express my great thanks to H. Benhallou the Chairman of the Institute of Earth Sciences at the University of Sciences and Technology Houari Boumediene for his support and assistance in my initial stage in his Institute after more than twenty-two years abroad. Thanks also to the administrative team of the Institute and my colleagues for their

curiosity, their kindness and for the useful and interesting scientific discussions. We thank my students Cheikh Moad and Saïch Boualem for their contributions to the collection of various data from diverse internet sites and catalogues.

#### *Appendix*

##### *Gutenberg's Relation or Frequency Magnitude for the Maghreb Region*




1. BOUGHACHA (2003) the number of events of magnitude larger than or equal to  $m_b$  occurring in a given region and for a certain length of time chosen accordingly is given for Algeria by the following relation. The data used are those of our current knowledge of the Algerian seismicity from 1891 to 1980.

$$\log N = 6.10 - 0.84m_b.$$

2. BENOUAR (1994) for the Maghreb using essentially the seismicity of the Tellian Atlas from 1900 to 1994:

Table 8

*Measured physical seismotectonic parameters for the three distinct Tellian Atlas tectonic blocks*

Parameters	Western Tellian Atlas	Central Tellian Atlas	Eastern Tellian Atlas
$\dot{M}_\Sigma$ [dynes-cm-year <sup>-1</sup> ]	$3.92 \times 10^{25}$	$3.92 \times 10^{25}$	$1.14 \times 10^{24}$
Mag_max	7.3	7.7	6.7
$\Delta t_{\max}$ [year]	89–94	375	172
Focal mechanism			
$\log(M_0) = cm_b + d$ [dynes-cm]	$1.5m_b + 16.28$ $c = 1.5 \pm 0.29$ ; $d = 16.28 \pm 1.56$	$1.5m_b + 16.28$ $c = 1.5 \pm 0.29$ ; $d = 16.28 \pm 1.56$	$1.02m_b + 18.69$ $c = 1.02 \pm 0.04$ ; $d = 18.69 \pm 0.27$
$\log(A) = m_b + b$ [cm <sup>2</sup> ]	$m_b + 5.61$ ; $b = 5.61 \pm 2.53$	$m_b + 5.61$ ; $b = 5.61 \pm 2.53$	$m_b + 6.25$ ; $b = 6.25 \pm ?$
$\log(D) = a_0m_b + b_0$ [cm]	$0.5m_b - 0.85$ $a_0 = 0.5 \pm 0.04$ ; $b_0 = -0.85 \pm 0.4$	$0.5m_b - 0.85$ $a_0 = 0.5 \pm 0.04$ ; $b_0 = -0.85 \pm 0.4$	$0.02m_b + 0.92$ $a_0 = 0.02 \pm ?$ ; $b_0 = 0.92 \pm ?$
$m_b = a_1 \log(L) + b_1(L)$ in [cm]	$1.99 \log(L) - 5.84$ $a_1 = 2 \pm 0.05$ ; $b_1 = -5.84 \pm 0.4$	$1.99 \log(L) - 5.84$ $a_1 = 2.0 \pm 0.05$ ; $b_1 = -5.84 \pm 0.4$	$\log(L) - 0.074$ $a_1 = 1.0 \pm ?$ ; $b_1 = -0.074 \pm ?$
$\log(N) = a - bm_b$	$5.96 - 0.82m_b$ $a = 5.96 \pm 0.14$ ; $b = 0.82 \pm 0.02$	$5.96 - 0.82m_b$ $a = 5.96 \pm 0.14$ ; $b = 0.82 \pm 0.02$	$2.2 - 0.85m_b$ $a = 2.2 \pm ?$ ; $b = -0.85 \pm ?$
$\dot{\epsilon}$	$\dot{\epsilon}_{\text{West}}$	$\dot{\epsilon}_{\text{West}}/1.5$	$\dot{\epsilon}_{\text{West}}/45$
$\beta$	0.54	0.54	0.83
$[\Delta \text{Sum}_D(t)/\Delta t]_{\max}$ [cm/year]. This is not a plate's velocity (see text)	24.1	21.4–22.4 region. 26.9 global (see text)	0.52

$$\log N = 5.96 - 0.82m_b.$$

For the overall Atlas mountain system :

$$\log N = 5.53 - 0.76m_b.$$

For Algeria:  $\log N = 4.72 - 0.65m_b$ .

3. MOKRANE *et al.* (1994) using Algerian seismicity from 1950 to 1992 by increments of

$$0.5 \log N = 5.58 - 0.78m_b.$$

4. HFAIEDH (1984) For the north of Tunisia (HFAIEDH, 1984) using the seismicity covering the period from 1900 to 1980:

$$\log N = 2.2 - 0.85m_b.$$

The absolute  $b'$  value calculated from data distributed over several years is smaller than the

one evaluated from the aftershocks sequences; which generally is closer to 1.0.

*Computing the Constant  $\beta$  Involved in Molnar's Formula (MOLNAR, 1979) and Characterising the Seismicity of a Given Region and its Seismotectonic Context:*

$\beta$  for the Eastern Tellian Atlas:

$\beta$  is computed from two equations: (1) The Gutenberg equation:

$$\log N = a' - b' m_b = 2.2 - 0.85m_b \quad (\text{HFAIEDH 1984})$$

and (2) from the empirical relation tying the moment  $M_0$  to the magnitude  $m_b$ , for the eastern Tellian Atlas; given by (22):

$$\log(M_0) = 1.02m_b + 18.69.$$

Therefore,  $\beta$  for the Eastern Tellian Atlas is of the order of  $\beta = b'/c = 0.83$

$\beta$  for the Western and the Central Tellian Atlas:

$\beta$  for the western and the central Tellian Atlas can be deduced from the following equations:

$\log N = 5.96 - 0.82m_b$  (BENOUAR, 1994) and Eq. 16

$$\log(M_0) = 1.5m_b + 16.28.$$

Therefore,  $\beta$  for the western and the central Tellian Atlas is of the order of  $\beta = b'/c = 0.54$ .

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