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Research article

Contribution of neotectonic and seismotectonic data in the study of induced seismicity in Sidi Salem dam

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Abstract
The seismic activity, which is related to the movements of tectonic plates, is called natural seismicity. However, the induced seismicity is a seismicity generated by human activity in a supposedly geologically stable environment. North Tunisia is one of important seismic region in the country. It is one of the most earthquake prone areas. This work aims to provide a new overview of seismotectonic studies in Tunisia and the contribution of this study in obtaining a detailed knowledge of the site of Sidi Salem dam and the process of triggering seismicity around this reservoir from 1982 to 2010. The maps in this study were georeferenced and digitized by ARCGIS 10.1 software. However, we analyzed the data of water level of the dam and the seismic activity by MATLAB. The results show that the current tectonic regime varies between a deformation in compression with a NW-SE direction and a deformation in sinister strike-slip fault. Compressive deformation characterizes northern Tunisia and it has been the source of shallow earthquakes. The seismicity of the Sidi Salem reservoir is an example of the initial seismicity, the earthquake that occurred in 1987 is linked to the first filling of the dam. An increase in seismic activity around the lake was observed from the year 1982 (date of the impoundment of the reservoir) until 2010 which is the chosen period in this work. These seismic events occurred following the seasonal increase in the water level of the dam, which has reached its maximum level several times.

Key words: Induced seismicity, Tectonic deformation, Sidi Salem dam, Tunisia.

1. Introduction

Natural seismicity is a seismic activity observed on a global scale, in relation to the movements of tectonic plates but also in a more diffuse manner, within or near pre-existing faults or discontinuities. Its engine remains tectonic forces. Natural seismicity is generally deeper, reaching several tens to hundreds of kilometers. However, induced seismicity is a seismicity generated by human activity in a supposedly geologically stable environment. It is associated with the creation of new faults or fractures. The studies of induced seismicity by human activities are becoming more common because of its high probability to destroy constructions and to cause human loss.

From this fundamental research perspective, the earthquakes induced by artificial lakes (dams) have the particular interest of being the closest to natural earthquakes. Indeed, the processes, which lead to seismicity, are either the filling of the dam or the increase of the pore pressure in the cracks of the rock mass.

The Tunisian territory represents the eastern end of the Maghreb domain and occupies a privileged geological position in Africa, since it is located between an immense deformed cratonic Saharan domain and an alpine domain in the North mainly deformed during the Mesozoic and the Cenozoic. The border between these two domains is highlighted by a broad alignment of faults and flexures stretching from Morocco to the Gulf of Gabes. In Tunisia, it is called the South Atlas accident (Gabtni et al. 2005). The observation of the catalog of seismicity in Tunisia shows seismicity characterized by moderate magnitudes. However, some events observed in the seismicity catalog of Tunisia are considered destructive. Seismic record from the installation of the National Seismological Network in 1976 until 2010, and neotectonic data allow to say that.

The Sidi Salem reservoir was built in Beja, a semi-arid region in Northwestern Tunisia. The studied artificial lake is an embankment dam with height of 73 m and volume of 814 Mm^3. The seismicity in the studied region has been controlled by seismic network operated by INM (National Institut of Meteorology). This dam is considered to have the potential of occurrence of reservoir induced seismicity with its structures. The construction of the dam finished in 1981. The first identified reservoir-induced events occurred in 1987 with magnitude of 5 after complete filling of the reservoir. The seismicity around the dam became increasingly frequent from the year 2003.

2. Material and methods

The fault stress analysis (Fsa) software was used to determine the current tectonic stress field in Tunisia.

ARCGIS 10.1 software was used to digitize the maps.

The data of water level of the dam and the seismic activity were analyzed by MATLAB (matrix laboratory), a programming language used for numerical calculation purposes.

3. Results and discussion

3.1. New overview of the neotectonic and seismotectonic studies in Tunisia

Induced seismicity by artificial water reservoirs was for the first time pointed out by Carder (1945) at Lake Mead in the United States of America. Damaging seismic events exceeding M 6 occurred at Hsinfengkiang, China in 1962; Kariba, Zambia–Zimbabwe Border in 1963; Kremasta, Greece in 1966; and Koyna, India in 1967 (Gupta 2002). In 10 December 1967, an earthquake of M 6.3 occurred at Koyna, it is the largest and most damaging reservoir triggered earthquake.

The Tunisian domain is formed following the convergence between Nubia and Eurasia which is responsible for folding and still active faulting. We used 62 earthquake focal mechanisms to constrain the present stress field of the Tunisian domain.

a- Focal mechanisms compilation

The Focal mechanisms for Tunisia and its surroundings were collected from different seismic catalogs as like as the Global Centroid Moment Tensor (GCMT) (Ekström et al. 2005), the Euro-Mediterranean Regional (RCMT), Havard CMT, ETH Zurich (Swiss Seismologic Catalog), the National Meteorology Institute Catalog (INM), and from the literature (Gueddiche et al. 1998; Bahrouni et al. 2013; Mejri 2012; Hfaiedh et al. 1985; Vannucci and Gasperini 2004; Ben Ayed and Zargouni 1990; Mezcua and Martınez Solares 1983). We collected 62 focal mechanisms located between longitudes 5.21 and 11.8E and latitudes 33.51 and 37.95N (Fig.1).

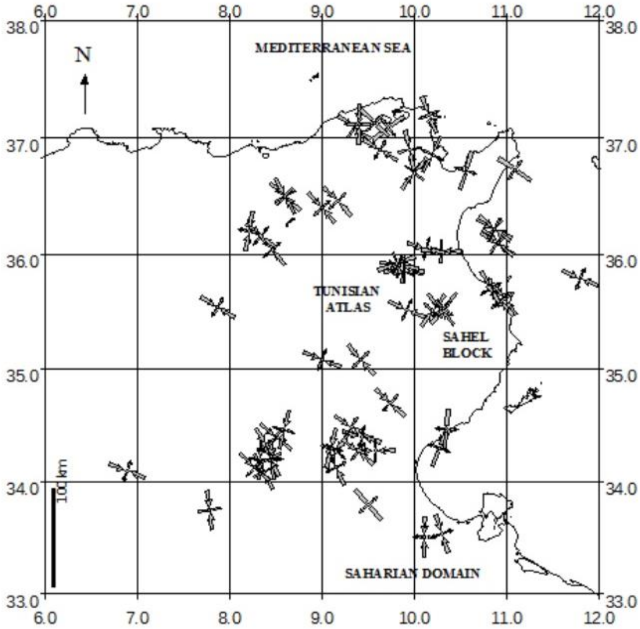

Fig. 1. Projection of the P, B, and T axes of the main earthquakes in the study area. Small open circles: epicenters; inward and outward pointing arrows: P and T axes; bar: B axes.

The magnitude of the events ranges from 2 to 6. We then analyzed these data with the Fsa software designed to handle fault slip data collected in the field (Burg et al. 1995; Heuberger et al. 2010) as well as focal mechanisms (Tajima and Célérier 1989).

b- Stereographic projection of P, B and T axes

The stereographic projection of the P, B and T axes shows subhorizontal P axis and especially B axis, but also some T, subvertical axes (Fig.2).

The majority of the P axes of the focal mechanisms are sub horizontal (close to the fundamental circle); also, the B axes are sub horizontal. On the other hand, the projection of the axes T is heterogeneous; we find vertical axes since they are closer to the center of the fundamental circle and we can find horizontal axes (Fig.2).

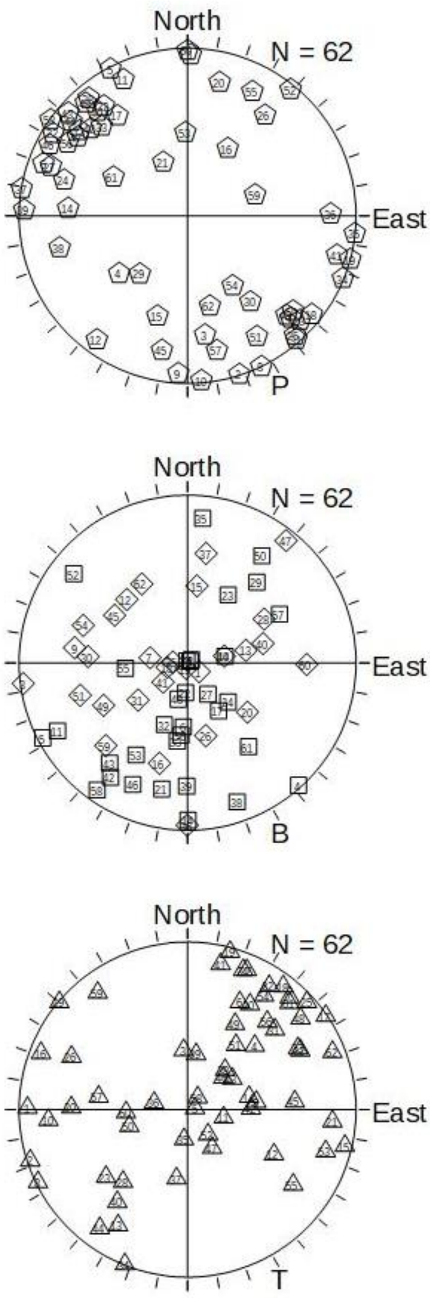

Fig. 2. Stereographic projection of P, B, and T axes of the focal mechanisms. Equal area lower hemisphere stereographic projection. B is represented by a square when going down and by a diamond when going up

According to the terminology of Célérier (2008), the distribution suggests a major wrench with a minor compressional tectonic regime. The maximum horizontal principal tends weakly to NW-SE. The maximum horizontal principal stress orientation is closest to horizontal and mapped in Fig. 2. This shows some degree of local consistency with significant regional variations.

c- Strike, dip, and rake distribution of the nodal planes

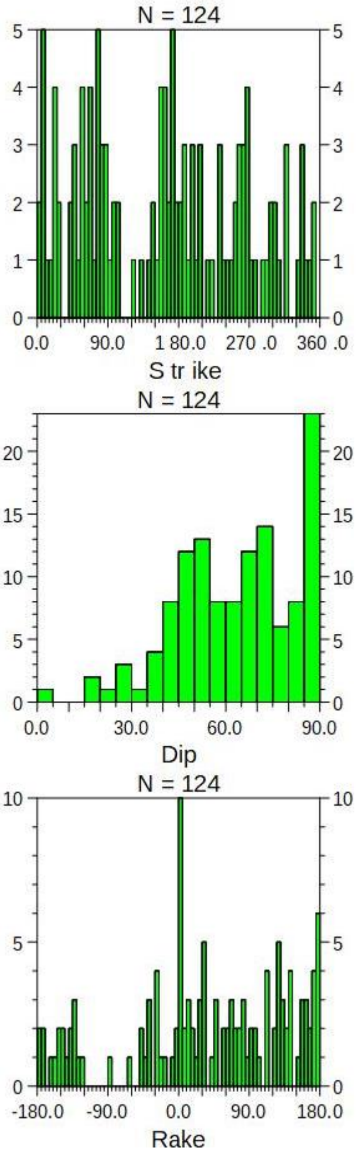

Fig. 3. Histograms of the strike, dip, and rake for both nodal planes of the focal mechanisms. Strike is chosen so that dip is to the right. The rake distribution maximum corresponds to left lateral strike slip events

The figure 3 is composed of 3 diagrams, the first diagram represents the direction (strike) of the nodal planes of the different focal mechanisms used in this work; the second diagram represents the dip of these planes and the third represents the inclination (rake). The nodal planes dip with an angle ≥ 45° NW since most of the planes in the second diagram dip with an angle between 45° and 90° (Fig.3). The third diagram, which represents the rake distribution for both nodal planes together, displays maxima almost equal to 0 corresponding to a strike-slip (Fig.3). The distribution of strike, dip and dip mainly shows strike-slips and reverse faults.

d- Classification of focal mechanisms using Frohlich diagram

The triangular diagram of Frohlich (1992) is a graphical representation focal mechanism as a function of the plunge angles of their P, B, and T axes. With this diagram, we can visualize the distribution of normal, reverse, and strike-slip focal mechanisms. Normal faulting corresponds to subvertical P axes (plunge > 60°), reverse faulting to subvertical T axis (> 50°). However, strike slip faulting corresponds to B axes with a wide range of plunges and plots near the vertical mediator (Célérier et al. 2012). The Frohlich diagram shows a distribution extending from the wrench to the compressional regime (Fig. 4), which is consistent with the stereographic projection of P, B, and T axes (Fig. 2).

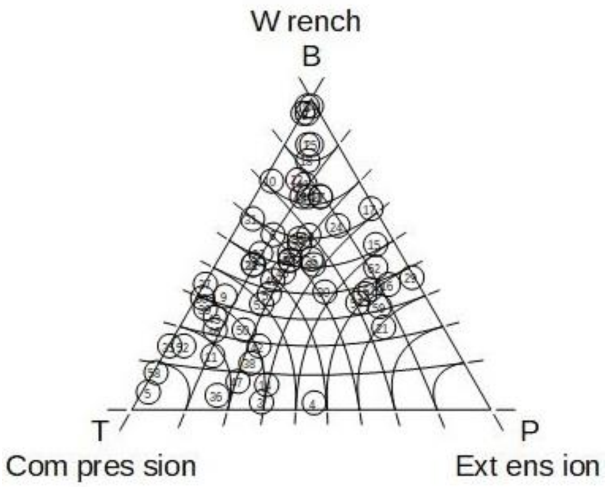

Fig.4. Triangular representation of the P, B, and T axes

e- Tunisia seismogenic areas

In Tunisia, the observable feature in the distribution of focal mechanisms is their dependence on depth. To better identify the different Tunisian seismogenic areas, we referred to the focal mechanism depth distribution. According to Imanishi et al (2011), the shallow part of the seismogenic zone is dominated by reverse faulting combined with strike slip faulting earthquakes; however, the wrench regime characterizes the depth part. Based on the results of Jallouli and Mickus (2000), which classified the Tunisian domains into different classes according to their crustal nature and also on the classification of focal mechanisms in the Frohlich diagram (Fig. 4), we can deduce that: In the North, under the Numidian flysch and Tellian units, the seismicity is characterized by a mix of reverse and strike slip faulting. This is due to the reactivation of reverse and thrust faults during the Quaternary (Bahrouni et al. 2013). This allows to classify northern Tunisian domain as an area of convergence with a thin crust and a shallow Moho (Fig. 5). The central Atlas contains NE trending fold axes. This zone is characterized by low seismicity. The few earthquakes are aligned over E-W and N-S faults which are formed during the tectonic activity of the Cretaceous (Soumaya et al. 2015) and reactivated in the Quaternary. However, this area shows the predominance of strike slip faults, so it is a deep seismogenic area with a thick crust and deep Moho (Fig. 5). The southern Tunisian Atlas is formed by E to NE thrusts and trending fold axes and NW to WNW strike-slip faulting (Gharbi et al. 2015), probably inherited from the Trias and Jurassic to middle Cretaceous (Gharbi et al. 2013). This zone is divided into three tectonic domains: the Metlaoui-Gafsa chain, the Chott chain, and the Saharian platform domain: The Metlaoui-Gafsa chain contains an E to ENE anticlines. These anticlines interfere with the NW fault system of Gafsa which was inherited from the Triassic and Jurassic rifting periods (Gharbi et al. 2015). This chain is characterized by thick sediments dating back from Cretaceous (Said et al. 2011). The Chott basin is formed by two synclines filled by Quaternary sediments: the western Chott El Jerid and the eastern Chott El Fejej (Gharbi et al. 2015). In the Chott chain, we find two major NW to WNW trending faults (Gharbi et al. 2013). The Sahara platform contains thick and weak folded Paleozoic sediments (Jallouli and Mickus 2000). These sediments are composed of continent deposits. The seismic data show that southern Tunisian Atlas is characterized by the dominance of the strike-slip faulting earthquakes, this is due to the reactivation of the ancient deep faults such as Gafsa and Northern Chott chain during the Quaternary (Bahrouni et al. 2013; Gharbi et al. 2014). So, the southern of Tunisia is a deep seismogenic area (Fig. 5)

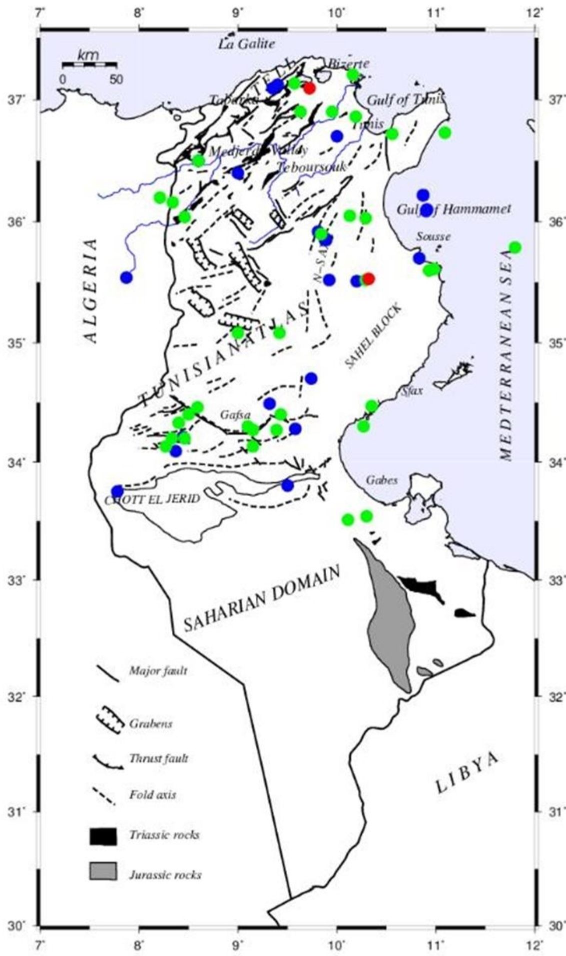

Fig. 5. Spatial discussion of focal mechanisms in different Tunisian domains (modified from Jallouli and Mickus 2000). Blue circles represent reverse faulting mechanisms, green circles represent strike slip faulting mechanisms, and the red circles represent normal faulting mechanisms

3.2. Seismotectonic context of Sidi Salem dam

The Sidi Salem reservoir was built in the state of Beja, a semi-arid region in Northwestern Tunisia. This region is characterized by fold-and-thrust series. It is a collision front which is part of the Maghrebides chain. This front is dominated by a NE-SW thrust faults. It is composed of diapiric folds aged upper Tortonian and which have been accentuated during the Quaternary compressive phase (Ben Ayed 1993, Meghraoui and Pondrelli 2012). Gueddiche et al (1998) showed in their reflection seismic campaigns in the Tell and Diapirs zones that the recent deformations mainly take place along thrust faults with direction NE-SW.

If we focus on the seismotectonic context of the study area, we find that the active fault directions which are the directions of the two nodal planes of the majority of the focal mechanisms reflect a NE-SW compressive deformation.

The Sidi Salem dam site is located on the last topographic tightening Mejerda Valley at a synclinal structure inter Diapiric River el Melah. The tectonic contacts through the retaining sides upstream and downstream of the dam, some of which are dotted with Trias, suggest that the full pressure of the reservoir stood at these tectonic contacts. This is a very important seismotectonic context which had a predominant effect of causing the seismicity induced by the reservoir.

Geographical and geological setting of the study dam

The Sidi Salem dam site is located about 70 km West-South-West of the city of Tunis and almost 4.5 km NW of the city of Testour and it is limited by 36°35'27 " North and 9°23'51" East. This dam was built at the intersection of the Medjerda with the El Melah, Khalled and Siliana rivers. The reservoir of Sidi Salem dam on Medjerda valley is the centerpiece of water mobilization of northern Tunisia in an interconnected system ensuring the security and sustainability of the country's economic infrastructure. The construction of the dam finished in 1981. The Sidi Salem dam is an embankment dam with height of 73 m and volume of 814 Mm^3. It was built to protect the lower valley against floods, for water supply, for irrigation, and for power generation.

The site of Sidi Salem is in the defile cleared by the Medjerda, more exactly on the side of an anticlinal structure affecting alternations of sandstone and marl of Miocene age. Downstream of the site, on the left bank, the complex structure of the alignment of Teboursouk is limited by Nummulite limestones of Eocene age of Jbel Skhira. These structures outcrop farther north and are packed into the Miocene terrains to form scales. On the right bank, the Miocene age lands are located against a complex structure of the Triassic mountains of Teboursouk dotted by the diapir of Oued Melah. Upstream of the dam site, there is, on the contrary, a regular monoclinal structure. The layers that correspond to the NW-SE parade of the dam, are parallel to the straight alignment of the valley. These layers plunge towards the left bank with a slight dip (about 20°) (Fig.6).

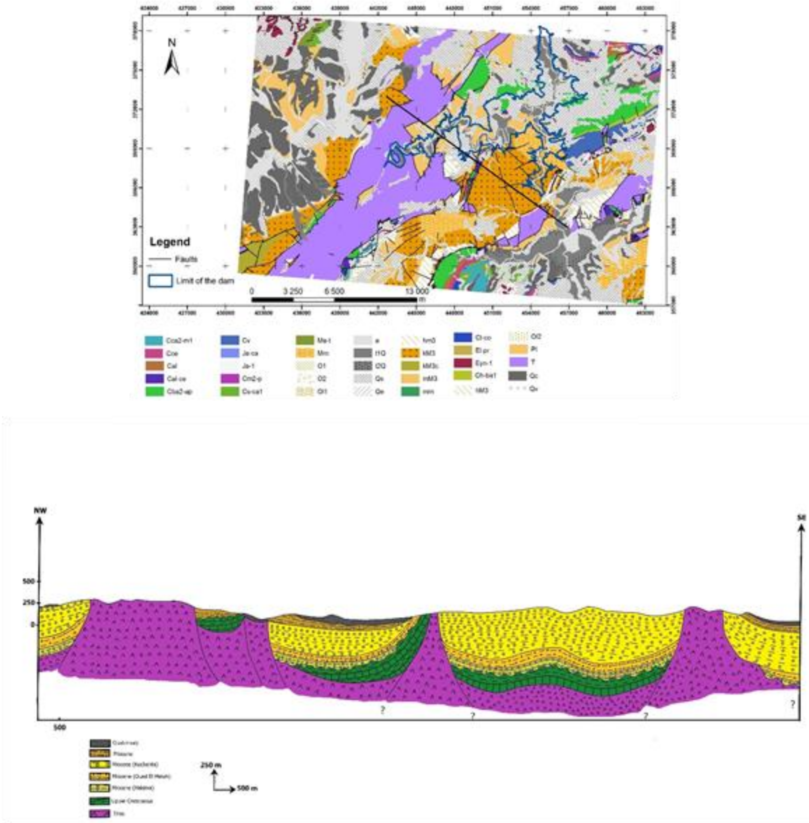

Fig. 6. General structure of the Sidi Salem dam site

3.3. Seismicity around the dam

Around the dam, seismicity is monitored by INM (National Institute of Meteorology) network seismic stations. The events used for this work dated from 1976 until the year 2010. This period of time was chosen because the network became more refined from the year 1976 by the installation of many recorded seismic stations. The magnitude of all events used in this study is greater than 2. The seismicity around the artificial lake is far from be negligible. The number of events recorded before the impoundment, i.e. from the year 1976 to the year 1981, reached 248 events around 100 km from the dam (Fig.7). The figure 6 shows that the seismicity is not very important, the most earthquakes are of low magnitude (M <= 2). To the east of the dam, the number of seismic events is greater than to the west. This is explained by the association of the seismic events with the major accident at Teboursouk, the active fault of Sidi Thabet, the Utique fault. In addition, during the 1980s, the Mejez el Bab region recorded several earthquakes at Jbel Bou Mousse.

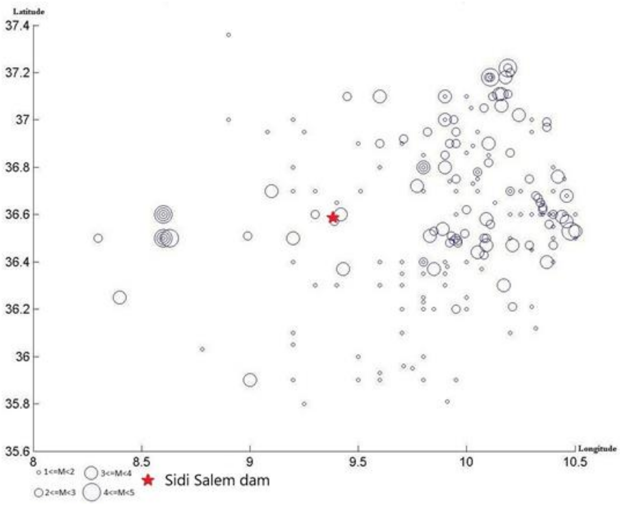

Fig. 7. Seismicity map before impoundment with different magnitudes within a radius of 100 km around the dam

In the other hand, seismic had increased after the impoundment, the number of events reached 684 during the period 1982-2010. The events that are close to the dam within a radius of 10 km around the reservoir have a magnitude that varies between 2 and 4. During this period, the number of events is important both to the west and east of the dam. The increase in seismicity west of the reservoir after the impoundment can justify that the Sidi Salem dam induce seismicity. We also notice the presence of two earthquakes of magnitude 3 and 4 less than 5 km from the dam (Fig.8).

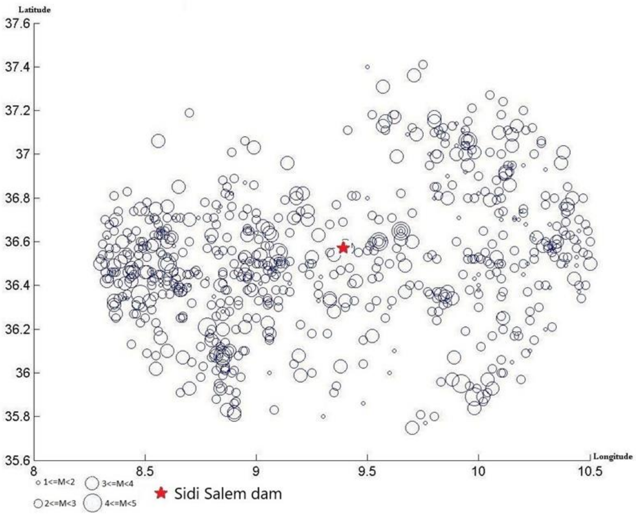

Fig. 8. Seismicity map after impoundment with different magnitudes within a radius of 100 km around the dam

Although, these results are not directly comparable because the period chosen for this study extends from the year 1976 to the year 2010. From 1976 to 1982 which is the date of the impoundment of the dam, the recorded seismicity took place 6 years before the impoundment. However, the events after the impoundment are events of 28 years (1982- 2010). So, to have comparable results, we normalized the number of events.

3.3.1. Normalization of the number of events

To confirm that the seismicity increased after impoundment, we neglected the time factor. This is done by dividing the number of events per month for the chosen period by the maximum number of events per month at different magnitudes. The number of events at different magnitudes is more frequent after the impoundment of the dam (Fig.9).

For figures 9, a peak in 1999 is very clear. In this year, there were several seismic events. The magnitude of the earthquakes that took place after the impoundment of the Sidi Salem dam is M > =2 and M >= 4.

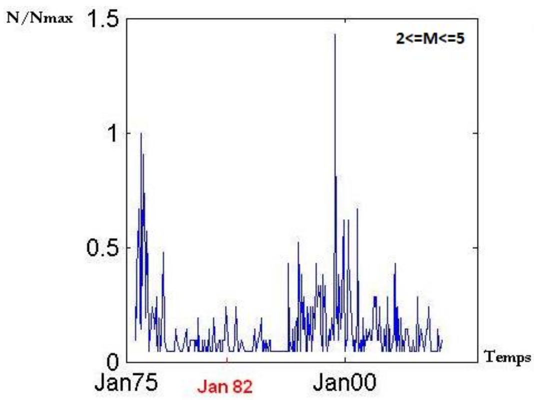

Fig. 9. N / Nmax = f (time) for different magnitudes within a radius of 100 km around the dam with: N / Nmax = Number of events per month divided by the maximum number of events per month

3.3.2. Seismicity within a radius of 15 km around the dam

30 seismic shocks occurred after the filling of the reservoir within a radius of 15 km around the dam. Among these events, we find 5 seismic events are very close to the dam. The last earthquake recorded in the period chosen for this study, was occurred in July 2009, with magnitude of 3.3 on the Richter scale and 5 Km for depth. This event took place 1 km from the Sidi Salem dam.

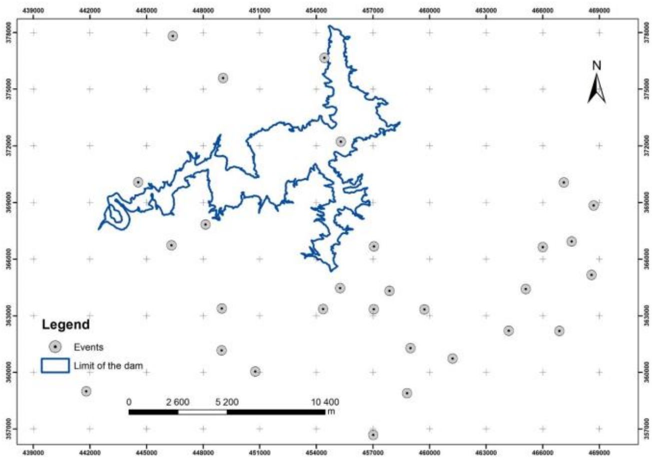

Fig. 10. Seismicity within a radius of 15 km from the Sidi Salem dam for the period (1982-2010)

3.3.3. Seismicity and water level

The seismic activity around 15km of the dam appears to be related to the complete filling of this reservoir. However, seismic shock occurred in 1987 with a magnitude of 5.0 after a complete filling of the reservoir (Total net input to Sidi Salem for the hydrological year 1986-1987 more than 725 hm3 with a water level 109 m exceeded during 4 months: February, March, April, May). The earthquake's epicenter which took place in September 1991 with magnitude 3.3, was located at the level of the Trajan Bridge at the Sidi Salem retaining tail. This seismic event follows a particularly wet hydrological year 1990-1991 (Water level of the dam was varying between 109.96 m in April 1991 and 108.24 m in August 1991). The seismic activity has increased considerably from the year 2003. The normal water level of the dam reservoir (110 m), which is fixed by the threshold of the spillway (Tulipe), was elevated to 115 m in autumn 1999. This New level was reached and exceeded several times in particular in January 2003 (dimension 117.51 m). The floods of this year have accumulated more than one billion cubic meters of water in Sidi Salem. During this year, the Sidi Salem's reservoir reached 117.51 m for the first time since the impoundment of the artificial lac, ie 2 m below the highest exceptional water level (119.5 m). In 2009, two seismic events occurred at a very close distance from the dam with magnitude of 3.5 both. In this year, the water level in the reservoir exceeded 117 m (Fig.11).

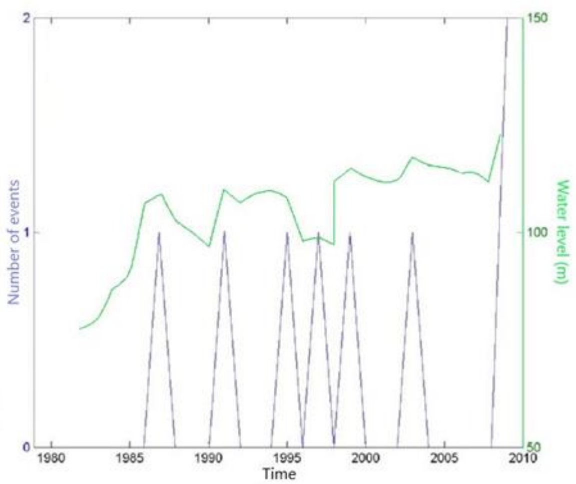

Fig. 11. Correlation between the number of events within a radius of 15 km around the dam and the variation in the water level of the dam as a function of time for the period (1982-2010)

To better understand the relationship between the water level in the dam and the number of events within a radius of 15 km from the reservoir, we correlated the seismic activity and the water's fluctuation as a function of time. This correlation was performed using Matlab. The graph shows that the number of events increases every time when the variation of the height of water increases and the height decreases when the number of events decreases. The first peak corresponds to the complete filling of the reservoir in 1987 (Fig 12). But the peak of 1998, does not coincide with water's fluctuation, it is a natural earthquake which is not induced by the dam.

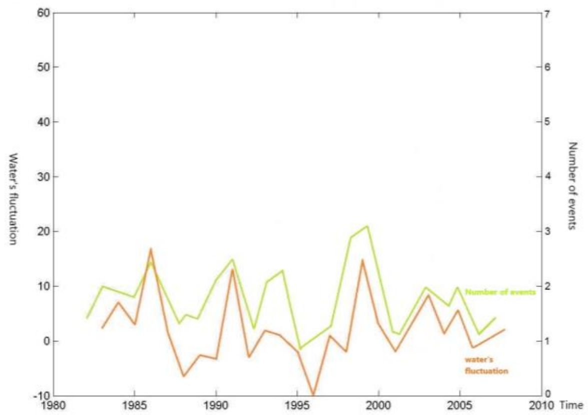

Fig. 12. Correlation between the water's fluctuation and the number of events 15 km around the dam for the period (1982-2010)

We suggest that this seismic activity resulted from the moment effect of loading of the reservoir and the postponed effect of pore pressure diffusion. The seismicity around the dam appears in relation to the water level in the dam. Monitoring microseismic activity using a local monitoring network remains an important tool in managing the risk of induced seismicity. Unfortunately, the study dam is the largest dam in the country and despite its importance, there is not seismic monitoring stations in the vicinity of the dam which allow us to determine seismic activity under 2 in magnitude and microseismic activities.

4. Discussion

The current stress regime can be explained by the geodynamic evolution of Tunisia. From the late Cenozoic to the present, the tectonic regime and strike shortening of Tunisia is influenced by the Africa-Europe collision in the north and by the rupture of the Sicily basin in the east (Billi et al. 2011; Nocquet 2012; Serpelloni 2010). This structural context is explained by the reactivation of inherited major accidents.

We referred to Soumaya et al. 2015; Gharbi et al. 2014; Gharbi et al. 2015; Gaieb et al. 2017 in order to understand the seismotectonic context of the Sidi Salem reservoir. The reservoir is located in the northwest of Tunisia, this region is characterized by a series of folds and reverse faults. It is a collision front which is part of the chain of the Maghrebides. This front is dominated by reverse faults trending NE-SW.

The Sid Salem dam is the biggest reservoir in Tunisia. It plays an important role in water mobilisation of northern Tunisia ensuring the security and sustainability of the country's economic infrastructure.

The seismic activity occurred in the area is characterized by shallow depth (the depth of seismic shocks is ranged from 1 to 5 Km). The seismic data in the period from 1976 until 2010 and in radius of 15 Km around the dam, showed that the number of events increased after the impoundment of the reservoir. The increasing of seismic activity at Sidi Salem reservoir for the chosen period seems to be associated to seasonal increasing of the lake water level. The correlation between the seismic activity and the water's fluctuation is clear.

5. Conclusion

The stereographic projection of P, B, and T axes calculated from focal mechanisms and the strike, dip, rake distribution of the faults, and slip show that the current tectonic regime varies between a compressive deformation trending NW-SE and a sinister wrench deformation.

The compressional deformation characterizes northern Tunisia and has been the origin of shallow earthquakes.

The seismicity at Sidi Salem reservoir seems to be an example of initial seismicity (Talwani 1997), the seismic event which took place in 1987 is related to the first filling of the dam. An increase of seismicity around the lake has been noticed after the impoundment of the reservoir. These events follow the seasonal increasing of the dam water level which reached its maximum several times.

The absence of seismic monitoring stations in the vicinity of the dam doesn't allow us to determine seismic activity under 2 in magnitude and microseismic activities. Hence, it is necessary to install seismic stations at different points of the lake. These devices are necessary to obtain quantitative data and allow us to follow the micro-seismic activity around the dam. Thus, the obtaining of numerous data will allow us to make more detailed analysis concerning the seismicity induced by the Sidi Salem dam and subsequently to make models (Pavlou et al. 2016).

References

Bahrouni N., Bouaziz S., Soumaya A., Ben Ayed N., Attafi K., Houla Y., El Ghali A., Rebai N. (2013) Neotectonic and seismotectonic investiga tion of seismically active regions in Tunisia: A multidisciplinary approach. J Seismol 18, pp235–256

Ben Ayed N., Zargouni F. (1990) Carte sismotectonique de la Tunisie à l'échelle 1/1000 000. Fondation Nationale de la Recherche Scientifique, Tunisia

Ben Ayed N. (1993). Evolution Tectonique de l'Avant-pays de la Chaîne Alpine de Tunisie du Début du Mésozoïque à l'Actuel. Ann. Mines et Géol. Tunisie 32, pp 286

Billi A., Faccenna C., Bellier O., Minelli L., Neri G., Piromallo C., Presti D., Scrocca D., Serpelloni E. (2011) Recent tectonic reorganization of the Nubia–Eurasia convergent boundary heading for the closure of the western Mediterranean. Bull Soc Geol Fr 182:279–303

Burg JP., Célérier B., Chaudhry N.M., Ghazanfar M., Gnehm F., Schnellmann M (2005) Fault analysis and paleostress evolution in large strain regions: methodological and geological discussion of the southeastern Himalayan fold-and-thrust belt in Pakistan. J Asian Earth Sci 24:445–467

Célérier B (1988) How much does slip on reactivated fault plane con strain the stress tensor ? Tectonics 7:1257–1278. https://doi.org/10. 1029/TC007i006p01257

Célérier B (2008) Seeking Anderson's faulting in seismicity: A centennial celebration. Rev Geophys 46:1–34

Célérier B, Etchecopar A, Bergerat F, Vergely P, Arthaud F, Laurent X (2012) Inferring stress from faulting: From early concepts to inverse methods. Tectonophysics 581:206–219

Ekström G, Dziewonski AM, Maternovskaya NN, Nettles M (2005) Global seismicity of 2003: Centroid-moment tensor solutions for 1087 earthquakes. Phys Earth Planet Inter 148:327–351

Frohlich C (1992) Triangle diagrams: Ternary graphs to display similarity and diversity of earthquake focal mechanisms. Phys Earth Planet Inter 75:193–198

Gabtni H, Jallouli C, Mickus K, Zouari H, Turki MM (2005) Geophysical constraints on the location and nature of the north Saharan flexure in southern Tunisia. Pure Appl Geophys 162:2051–2069

Gaieb, S., & Jallouli, C. (2017). New overview of the neotectonic and seismotectonic studies in Tunisian domains. Arabian Journal of Geosciences, 10(22), 1-11.

Gharbi M, Masrouhi A, Espurt N, Bellier O, Amari EA, Ben Youssef M, Ghanmi M (2013) New tectono-sedimentary evidences for Aptian to Santonian extension of the cretaceous rifting in the northern Chotts range (southern Tunisia). J Afr Earth Sci 79:58–73. https://doi.org/10.1016/j.jafrearsci.2012.09.017

Gharbi M, Bellier O, Masrouhi A, Espurt N (2014) Recent spatial and temporal changes in the stress regime along the southern Tunisian front and the Gulf of Gabes: New insights from fault kinemat ics analysis and seismic profiles. Tectonophysics 626:120–136

Gharbi M, Espurt N, Masrouhi A, Bellier O, Amari A (2015) Style of Atlassic tectonic deformation and geodynamic evolution of the southern Tethyan margin, Tunisia. Mar Pet Geol 66:801–816

Gueddiche M, Ben Ayed N, Mohammadioun G, Mohammadioun B, El Ghali A, Chekhma H, Diament M, Dubois J (1998) Etude sismotectonique de laTunisienord-orientale. Bull Soc Geol Fr 169: 789–796

Heuberger S, Célérier B, Burg JP, Chaudhry NM, Dawood H, Hussain S (2010) Paleostress regimes from brittle structures of the Karakoram Kohistan suture zone and surrounding areas of NW Pakistan. J Asian Earth Sci 38:307–335

Hfaiedh M, Ben Ayed N, Dorel J (1985) Etude néotectonique et sismotectonique de la Tunisienord-orientale. Note Serv Géol Tunisie 16:41–56

Imanishi K, Takeda N, Kuwahara Y, Koizumi N (2011) Enhanced detecion capability of non-volcanic tremor using a 3-level vertical seismic array network, VA-net, in southwest Japan.

Jallouli C, Mickus K (2000) Regional gravity analysis of the crustal structure of Tunisia. J Afr Earth Sci 30:63–78

Meghraoui M., Pondrelli S. (2012). Active faulting and transpression tectonics along the plate boundary in North Africa. Ann. Geophys. 55. doi:10.4401/ag-4970

Mejri L, (2012). Tectoniquequaternaire, paléosismicitéet sources sismogéniquesenTunisienord-orientale: étude de la faille d'Utique. Thèse Doc. Univ. Toulouse, pp 184

Mezcua J, Martınez Solares J (1983). Seismicity of the Ibero–Maghrebian area Instituto Geográfico Nacional Report, Madrid

Nocquet JM (2012) Present-day kinematics of the Mediterranean: A comprehensive overview of GPS results. Tectonophysics 579:220–242

Pavlou K., Drakatos G., Kouskouna V., Makropoulos K., Kranis H. (2016). Seismicity study in Pournari reservoir area (W. Greece) 1981-2010. J. Seismol. doi: 10.1007/s10950-016-9552-1

Said A., Baby P., Dominique C., Ouali J. (2011) Structure, paleogeographic inheritance, and deformation history of the southern atlas foreland fold and thrust belt of Tunisia. Tectonics 30. https://doi.org/10.1029/ 2011TC002862

Serpelloni E., Vannucci G., Pondrelli S., Argnani A., Casula G., Anzidei M., Baldi P., Gasperini P. (2007) Kinematics of the western Africa Eurasia plate boundary from focal mechanisms and GPS data. Geophys J Int 169:1180–1200

Soumaya A., Ben Ayed N., Delvaux D., Ghanmi M. (2015). Spatial variation of present-day stress field and tectonic regime in Tunisia and surroundings from formal inversion of focal mechanisms: Geodynamic implications for central Mediterranean. Tectonics. doi:10.1002/2015TC003895

Tajima F, Célérier B (1989) Possible focal mechanism change during reactivation of a previously ruptured subduction zone. Geophys J Int 98:301–316. Geophys Res Lett 38

Talwani, P. (1997). On the nature of reservoir-induced seismicity. Pure and applied Geophysics, 150(3), 473-492

Vannucci G, Gasperini P (2004) The new release of the database of earthquake mechanisms of the Mediterranean area (EMMA version 2). Ann Geophys 47:307–334