EVIDENCE OF THE INVOLVEMENT OF STRUCTURAL PREDISPOSITIONS OF THE CRYSTALLINE BASEMENT IN THE OBSERVATION OF MICROEARTHQUAKES IN THE WADI FIRA IN EASTERN CHAD

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Abstract: The seismically active regions of the world are modelled on zones where the crust is constantly evolving, subduction zones or seismically active zones such as the East African Rift. Chad is not one of these zones, because towards the end of the Precambrian, Chad's crustal evolution came to an end and it became part of a stable zone. Nevertheless, micro-earthquakes of up to magnitude four have been recorded in the Wadi-Fira region thanks to the Abéché ABC seismological station. The signals recorded have been processed and located in an area of very uneven high basement at the surface. Their origin is thought to be linked to the dynamics of the aquifer in relation to the rate of weathering, which plays an important role in the infiltration of water, causing the hydrostatic pressure to vary considerably. This variation in pressure can lead to a change in the state of stress in pre-existing faults. An increase in fluid pressure in the rock mass can create fault instability. The largest recorded event is located on the N30°E direction corresponding to the direction of an old non-active fault representing the Volcanic Line of Cameroon.

Keywords: Near earthquakes, epicentre, regional phases, Wadi Fira (Chad).

I. INTRODUCTION

Many seismic events occur throughout the world every year, on the order of a thousand, most of which are not perceptible to human sensibility. Generally speaking, these events are perceived from the outset as the result of tectonic events, and therefore natural. From this point of view, they are among the most catastrophic natural phenomena, one example being the very violent earthquake of 21 May 2003 in Algeria, which killed more than 2,000 people and injured thousands more.

Located in a stable zone after the Pan-African orogeny, Chad has not experienced any devastating seismic events, although there are tectonic faults crossing the country [1] [2]. The risks of a seismic scenario as described above are very low. However, thanks to the Abéché Seismic Centre, which has been in operation since 1962, earthquakes of small magnitude have been recorded in localities relatively close to each other in the east of the country, particularly in the province of Wadi-Fira.

The June 2015 seismic crisis in the Wadi-Fira region was the first of its kind to be felt by the population [3]. These earthquakes, even if localised and small in scale, require serious attention in view of the enormous potential for destruction that such a phenomenon can demonstrate.

The Abéché seismological station (ABC) in eastern Chad operates a mini network of eight short-period sensors and one three-component sensor. Previous comparative studies of data from ABC and the Review Event Bullen (REB) have shown that the station alone records 80% of the world's seismicity, which is an enormous amount. Locally, the signals recorded are few in number and of very low magnitude (around 3), mostly resulting from quarry blasting.

Suddenly, in 2015, a seismic crisis was felt by the local population in the Wadi Fira region. Since then, seismic activity has been observed in the region, prompting us to carry out in-depth studies to investigate the possible causes.

II. GEOGRAPHICAL CONTEXT

Located in the east of the country, Wadi-Fira province is bordered to the north by Borkou and Ennedi, to the south by Ouaddaï, to the east by Sudan and to the west by Batha (fig. 1). It covers an area of 52,228 Km2 [4] with a topography largely dominated by a plain of hydro morphic and highly fertile soils. The highest peak is in the south-east of the area, at around 1,302 m, compared with around 386 m for the lowest in the west, with the profile decreasing from the east to the west of the study area (Fig. 1). There are extensions of the granite reliefs of the Guéra massif and the Sila plateau [5].

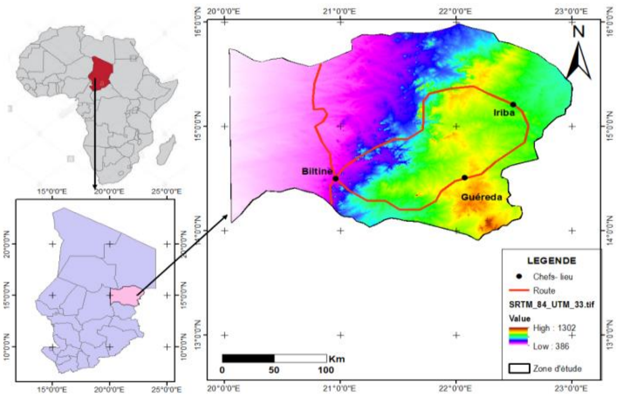


Fig. 1: Map of the study area

III. GEOLOGICAL AND GEOPHYSICAL APPROACH TO THE REGION

A. geological framework

Chad lies within a large area known as the 'Pan-African mobile zone' [6], formed during the Pan-African orogeny that took place during the Neoproterozoic (620 - 540 Ma). This mobile zone is bounded to the south by the Congo craton, to the west by the West African craton, to the north-east by the hypothetical Nilotic craton [7] or Central African phantom craton [8], the Eastern Sahara craton [9], the Saharan metacraton [10], or as a large Neoproterozoic belt containing no craton but characterised by the presence of 1.0 Ga basement rocks in Sudan [11] or even further away by the East African mobile zone bordering the Red Sea (fig. 3).

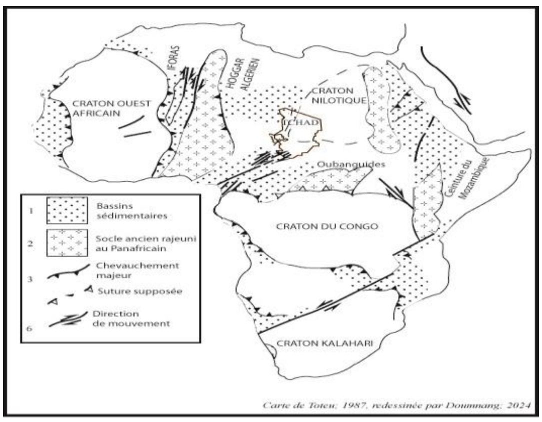


Fig. 2: Map of Pan-African cratons and formations

The Proterozoic formations correspond to crystallophyllian rocks and granitoids that outcrop mainly at the periphery of the Chad basin (fig. 4): at the northern end of the country (Tibesti). They outcrop from the Aïr in Niger to Libya [12], in the east (Ouaddaï) and in the Massif Central (Guéra). They are also found in the south-west (Mayo-Kebbi) and in the extreme south, in the Mbaïbokoum region, on the edge of the Oubanguides range.

The Ouaddaï massif, in eastern Chad, is one of the least-known regions of Africa in terms of its geological evolution. [13] consider that it is composed of Palaeoproterozoic basement rocks, while [10], [14] and [15] consider that it corresponds to the reworked south-eastern margin of the enigmatic Saharan metacraton made up of pre-existing Archean and Palaeoproterozoic crust. [16] propose that it is a Neoproterozoic juvenile crustal segment locally contaminated by the Palaeoproterozoic crust.

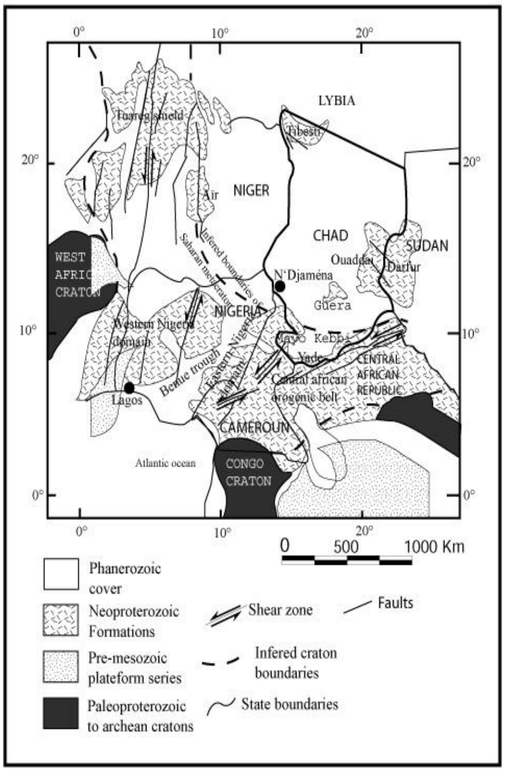


Fig. 3: Regional geological map

The geological formations of the Wadi-Fira region are mainly crystalline basement of Proterozoic age (Fig. 5) [17], [5]. This geology is that of the Ouaddaï massif with largely granitic Precambrian basement formations and volcanic and cover formations that extends westwards into Sudanese Darfur [18], [19] [20] [21]. The Precambrian basement formations are predominantly granitic but also include evidence of metamorphism and brittle tectonic vein rocks. The metamorphic formations only become significant to the south of the 13th parallel [22]. The intrusive rocks are synkinematic granitoids. They appear in elongated outcrops following structural directions that are generally south-west-north-east. Quartz veins are also common. They were formed as a result of events linked to the Pan-African orogeny and the tectonic events that affected the locality at the end of the Cretaceous period.

The geological map of the region shows that the veins have a preferred north-east-south-west direction, corresponding to the structural directions of the basement, and two secondary directions, respectively north-north-west-south-south-east and submeridian. The two main phases in the development of the vein systems certainly correspond to the Pan-African and Maastrichtian periods [23].

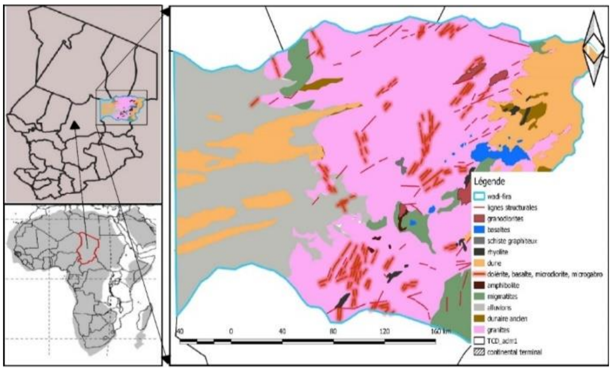


Fig. 4. Geological map of the study area

B. geophysics and seismicity

Geophysical studies in Chad began in 1954 with a short mission by a team from the Office de la Recherche Scientifique et Technique Outre-Mer (O.R.S.T.O.M), which became the Institut de Recherche pour le Développement (IRD) in 1984. The mission revealed a number of major gravimetric routes [24] and short-line electrical soundings [25]. Given the relatively limited resources deployed in relation to the surface area covered, the studies carried out could not go beyond the general reconnaissance stage, which is exactly what the O.R.S.T.O.M. had set itself. In 1959, electrical and seismic refraction surveys were carried out in search of water by the Compagnie Générale de Géophysique (C.G.G), the Bureau de Recherches Géologiques et Minières (B.R.G.M) and the Compagnie Française de Prospection Géophysique (C.F.P.G). The main geophysical work in Chad was undertaken in 1970 by [26]. This work was limited to reconnaissance by gravimetric surveys.

The main features highlighted are: (1) the large trench that crosses the whole of southern Chad (Doba, Baké-Birao, Salamat) and is located on the extension of the northern coast of the Gulf of Guinea, and (2) the large Sao-Tomé-Cameroon transverse line known as the ‘Cameroon line’, which extends as far as Tibesti via a diversion to the Erdis basin (Ounianga Kebir). This fault, which cuts across the whole of Chad from Cameroon to Tibesti, could be the result of thinning of the crust and upwelling of the upper mantle.

From a seismological point of view, research began in 2000, using data from the Chad station (ABC). The location of events restricted to the periphery of the African plate over a period of 3 years (2007 to 2010), and listed in Fig. 6, shows that Chad is located in a very stable zone from a tectonic point of view. The risk of earthquakes is therefore very low. This is consistent with previous studies of African seismicity [27], [28]. Nevertheless, it is worth noting the existence of small signals of very low magnitudes, mostly resulting from quarry blasting and therefore not shown in the figure.

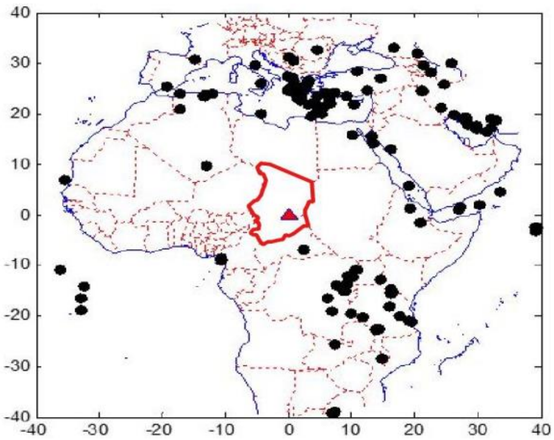


Fig. 5: Map showing the seismicity of Africa as seen from Chad. Source: CSA

However, events recognised as unexpected earthquakes [29] have already been recorded in the Sila, BET and Wadi-Fira (our study area) and even in Sudan at the end of the 1990s. Then in 2015, in June, a seismic crisis occurred in the Wadi-Fira region in the Ouaddaï massif, shaking the inhabitants of the region, who were surveyed.

C. knowledge of regional waves

Numerous studies have now been carried out to understand and interpret all the phases present on regional seismograms. Classically, the Pn, Pg, Sn, Sg and Lg phases are recorded. These phases are diffracted and refracted by the various heterogeneities they encounter along their propagation paths and thus form the secondary phases or coda of the seismogram. Figure 2 below shows the recording of the earthquake in southern Sudan, 300 kilometres north-east of the station.

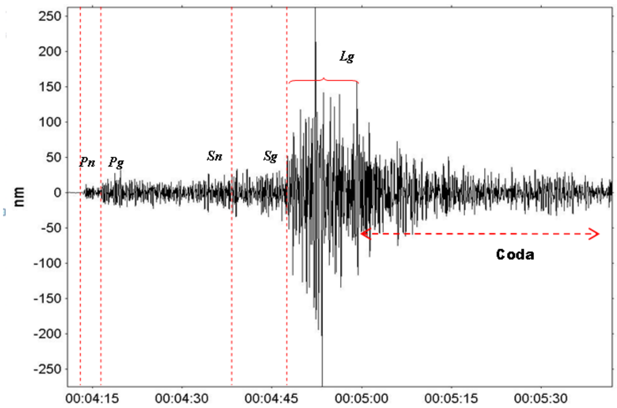


Fig. 6. Seismogram of the South Sudan earthquake located 300 km from the station.

On this recording, we can see the different phases mentioned above and we can also observe that each of these phases is followed by numerous arrivals, which alone carry a significant proportion of the energy of the seismogram. While classical wave trains are often well reproduced, the secondary phases, which owe their existence to the heterogeneity of the propagation medium, are generally more difficult to model [30]. This difficulty stems partly from our limited knowledge of the propagation medium and partly from our lack of understanding of the interactions between the wave field and the various heterogeneities in the medium. While we now know relatively precisely how velocity changes as a function of depth, lateral variations in velocity are more difficult to assess. Added to this is the difficulty of implementing numerical techniques capable of taking into account the three-dimensional propagation effects of the wave field [31]. For long propagation distances, the hypothesis of a spherical medium is generally verified, at least for the deepest layers of the Earth.

At regional distances, and for short-period waves, this hypothesis is no longer valid, since the wave field propagates essentially in the crust, which is a medium containing strong heterogeneous zones, with characteristic sizes comparable to the wavelength of the regional seismic phases. This results in significant deformations of the wave field, which contribute to the formation of the coda of the seismograms.

D. propagation parameters

We will consider that the phases present on the seismograms result on the one hand from the primary phases which had a direct propagation path between the source and the various receivers and on the other hand, from all the phases diffracted by the various heterogeneities which make up the propagation medium. The wave field recorded by a seismological antenna is then described by a superposition of plane waves:

$$s(\vec{r},t) = \sum_{\substack{1\leq j\leq q \\ 1\leq j\leq q}} A_{ij} e^{i(\vec{k}_{ij}.\vec{r}-2\pi f_i t+\varphi_{ij}(t))} + \mu(\vec{r},t) \qquad (1)$$

Where $\vec{r}$ (x,y) is the position vector of each of the sensors that recorded the wavefield, t is the time description variable. Around each time t and for each of the frequencies f_i ($1\leq i\leq p$) contained in the signal, q wavelets may be present, each characterised by its wave number vector k_{ij} (k_{ij_East}, $k_{\_ij\_North}$) and its amplitude A_{ij}. $\mu(\vec{r},t)$ is the noise contained in the seismograms [32] Adequate summation of the wave fields propagating through an antenna allows not only the detection of events of very low magnitudes but, at the same time, the estimation of the propagation parameters relating to these wave fields. These parameters are fully defined once we have estimated (1) the direction and (2) the apparent speed of the chad wave [33]. A plane wave $s(\vec{r},t)$ propagating through a seismological antenna is characterised by an oscillation frequency f_0 and a wavenumber vector k_0 :

$$s(\vec{r},t) = s_0 e^{i(\vec{k}_O \vec{r}-2\pi f_0 t)} \qquad (2)$$

where s_0 represents the amplitude of the wave. The parameters of this wave field will be fully defined once we have found the frequency f_0 and the wavenumber vector k_0 that govern its propagation. We will then be able to estimate the direction θ_0 of the wave, which represents its azimuth, and its apparent propagation velocity v_a :

$$\theta_0 = \arctan\left[\frac{k_{Est}}{k_{Nord}}\right] \quad \text{et} \quad v_a = \frac{2\pi f_0}{|\vec{k}_0|} \qquad (3)$$

θ_0 is the angle between the geographic north and the direction given by the wave number vector $\vec{k}_0$ characterising the wave propagation. k_{East} and k_{North} are the projections of the wave number vector onto the geographic axes oriented along the E-W and N-S directions. The real speed v of the wave is :

$$v = v_a sin i_0 \qquad (4)$$

where i_0 is the angle of incidence of the wave.

In this paper we are interested in nearby events, those whose epicentral distance is less than 100km. The phases involved are those shown in the diagram in figure 3 below, where the hypocentre is located at a depth h. As the crust is fairly homogeneous in the region, we use the velocity model for the Ivory Coast, based on data from the LAMTO station.

IV. MATERIALS AND METHODS

A. *materials*

For this work, we used:

- The soil map of [34] ;
- Geological map by [18] ;
- Hydrogeological map [23] ;
- The hydrogeological map of [35].

Four landsat 8 satellite images of different scenes (scene 1 (path: 180 and row: 049) of 15/04/2015, scene 2 (path: 180 and row: 050) of 15/04/2015, scene 3 (path: 181 and row: 049) of 22/04/2015 and scene 4 (path: 181 and row: 050) of 22/04/2015 downloaded from the USGS website. These scenes were used to produce an image covering the entire study area.

The station (ABC), as mentioned above, consists of a mini-array of eight short-period sensors. The geometry of the mini-network is a succession of interlocking triangles designed to locate seismic events at local, regional and teleseismic distances. The short-period seismometers used are of the ZM500 type, sensitive to the vertical component of the seismic wave. The stations are placed on well-rooted granite blocks, which ensures good coupling with the ground, good protection against atmospheric disturbances, mainly wind, and low influence of meteorology on the recordings. In addition, their distance from built-up areas and the sea means that industrial background noise and the permanent effect of sea swell, which propagates over very long distances, can be reduced as much as possible. This minimises the average background noise of the stations compared with the NLNM (New Low Noise Model) of [36] (fig. 7).

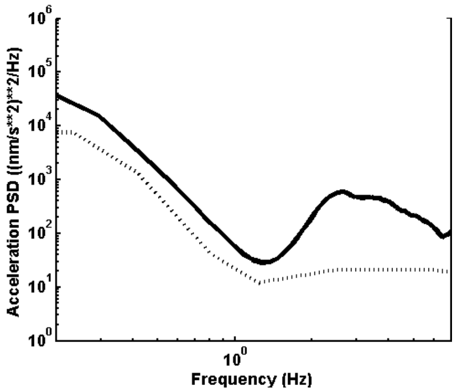


Fig. 7: Average background noise at station ABC (solid line) compared with the Peterson (NLNM) background noise model (dashed lines).

B. METHODS

Processing seismological data.

This is done in three stages:
- Data analysis: This is carried out using the 'JADE' software, which displays all the recordings for a given day on the screen and identifies the times corresponding to the actual signals.
- Data acquisition: the signals identified on JADE are acquired by specific software that puts them in a format ready for processing.
- Data processing: This is carried out by ONYX software, which is used to pinpoint the times of arrival of the waves, measure amplitudes and periods and carry out localisation.

Satellite image processing

Processing consists of pre-processing and actual processing.

Pre-processing using the SCP's atmospheric correction and pansharpenig tools of the four landsat 8 scenes before producing a raster image covering the whole of Wadi-Fira using the strip mosaic process, which was then used.

Processing consists of colour compositing the raster using RGB channels to highlight useful information.

The Land/Water CFC, TM5, TM6 and TM4 were used in this study to highlight the ground surface. To complete the exercise, we further improved the properties of the raster covering the area by adjusting the colour rendering parameters so as to obtain an image with better contrast, making it easier to extract the desired data, in this case the lineaments.

Lineament extraction

Once we had made the image easily usable, we proceeded manually to extract the network of lineaments by traversing the entire area. The tool for creating a new shapefile layer was used for the task. The result is a lineament map (fig. 9).

V. RESULTS

All the signals processed are listed in Table 1, in which, it should be remembered, only events of magnitude greater than 2 are represented.

Lat : 14.48N Lon : 20.82E 59km, prof : 10km, Ml = 4.5

The table below lists the events resulting from the 2015 crisis and located using ONYX software. As mentioned above, these are events with a magnitude greater than 2. The other signals recorded before and after 2015, for distances of less than 100 km, are from well-known quarries.

Table 1: List of events processed by ONYX

Date	Heure.Arr	Lon(°)	Lat(°)	Dist(km)	Ml	Az(°)	Rms
20/06/2015	19:32:10	20,81	14,36	64	4,45	98.7	0,07
7/06/2015	00:27:40	20,83	14,37	64	3,97	106.00	0,09
3/06/2015	13:42:00	20,83	14,36	64	3,47	108.2	0,09
5/06/2015	09:47:10	20,84	14,37	64	3,1	106.9	0,1
20/06/2015	22:14:00	20,83	14,37	65	2,99	105.3	0,09
3/06/2015	19:59:00	20,83	14,37	64	2,89	106.0	0,09
6/06/2015	00:39:00	20,83	14,37	64	2,79	105.9	0,1
3/06/2015	13:04:10	20,83	14,37	64	2,57	105.6	0,1
20/06/2015	20:14:00	20,83	14,37	64	2,46	105.5	0,09
21/06/2015	08:05:20	20,82	14,37	65	2,26	104.7	0,09
27/06/2015	18:45:30	20,83	14,36	64	2,12	106.7	0,1

Figure 9 shows the epicentre as a blue diamond, the sensors as blue circles and the villages affected by the earthquake as red triangles. Fortunately, there was no damage in these villages, but the tremor was strongly felt, especially in the village of Dougine, which is very close to a mountain.

The coordinates of the epicentres of the earthquakes in the province were overlaid on the map of the province, giving us a configuration as shown below, with a concentration of all these events in the southern part of the Biltine region (fig. 8).

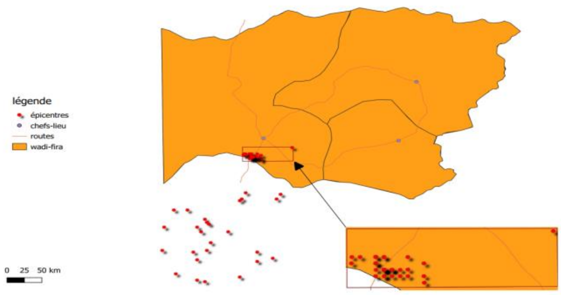


Fig. 8. Location of epicentres

A. satellite image processing results and interpretation

- The Landsat 8 scene processing chain has produced an improved image of an area that is sufficiently usable for the purposes of this study, as shown below.

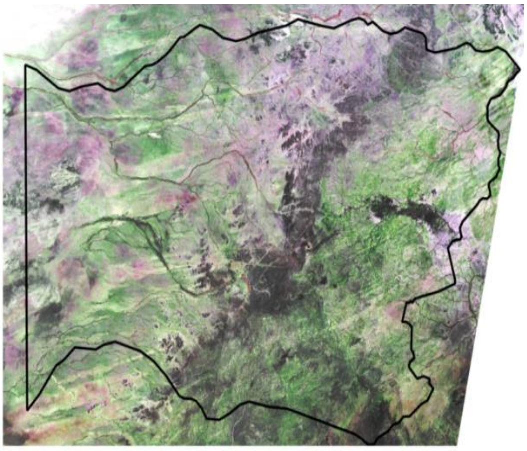


Fig. 9. TM5, TM6, TM4 colour composition of satellite images of the study area.

The resulting map of the lineament network is quite revealing in Figure 6.

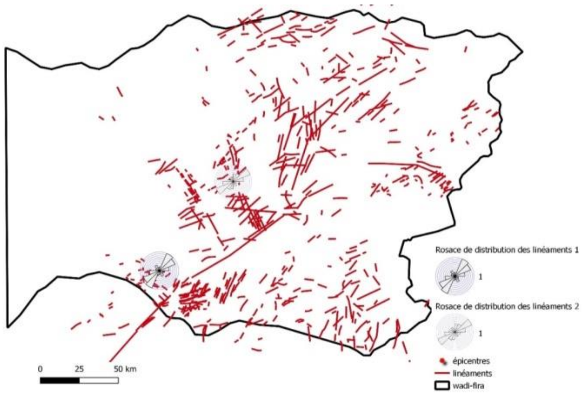
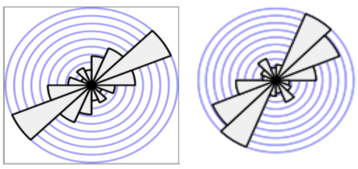


Fig. 10. lineament map

The distribution rosettes of the lineaments in the immediate area around the epicentres and that of the province give a relatively north-east-south-west orientation of the lineaments as shown below:



A **B**

Fig. 11. A. Rosette showing the distribution of lineament directions at Wadi-Fira. B. Rosette distribution of lineament directions in the immediate area around the epicentres

B. Superimposing the lineament map and the epicentre location map gives us the following

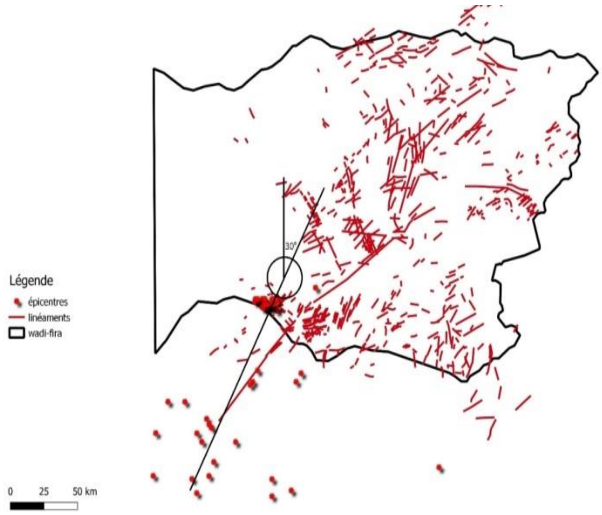


Fig. 12: Relationship between the distribution of lineaments and seismic epicentres

VI. DISCUSSION

The seismicity of the locality is characterised by small, very localised earthquakes with episodes of relatively very low magnitudes, with the exception of 2015 marked by the event of 20 June. The other years have been virtually calm, as pointed out by [3]: using data from the station before and after the event, we were able to conclude that this was an isolated earthquake.

The concentration of the highest magnitudes to the south of Biltine around the point at coordinates 14°22'4''N, 20°49'4''E could be explained by a particular structural configuration compared with the other localities subject to this phenomenon in terms of the state of fracturing of the crystalline basement. This possibility could be supported by the results of the work carried out by [37] on the fractured thickness, which shows that it is very high and therefore concludes that it would have played a very important role in the infiltration of water, and therefore the recharge of the aquifer.

At the scale of the entire Wadi-Fira region, the network of lineaments obtained highlights a major North-East-South-West direction, which could confirm the observations of [23] and a North-West-South-East direction [38].

It reveals that the geological map shows that the veins strike in a preferred north-east-south-west direction, corresponding to the structural directions of the basement. This was also noted by [17] in the southern part of the Ouaddaï massif as being the dominant direction. As noted by [39] in the Guéra, this direction also corresponds to the Tchollíré-Banyo shear direction in Cameroon.

The secondary directions N33°E and N78°E could respectively mark the traces of the Tertiary corresponding to the Volcanic Line of Cameroon (LVC N30°E) and the Pan-African (N70°), of the Adamaoua-Yadé shear zone [40].

To a lesser extent, we also note the NW-SE direction, which underlines the Palaeozoic (570 - 250 Ma); Hercynian tectonics is probably responsible for the rejection along a fault oriented North-West - South-East which marks the boundary between the Ouaddaï basement and the Erdis basin, [22] but also the Cretaceous; collapses caused by NW-trending normal faults on either side of Lake Chad [42].

In the immediate area around the seismic theatres, the lineament directions mark a main direction that relates to that of the LVC, N30°E, and a secondary north-east-south-west direction.

To some extent, the N78°E direction, which would still be that of the pan-African direction noted further in the centre of the country in the Hadjer Al Hider, Hadjer Bigli and Hadjer El Hamis alignment by [43].

Assuming that the line (D) is median to the set of epicentres of the events, we can consider its direction in relation to the direction of the North. This is approximately N30°E towards the East, which corresponds to the Volcanic Line of Cameroon.

The seismic manifestations could be due to small ruptures in the N30°E direction which would not be the result of regional dynamics but of disturbances of local origin. These disturbances could be linked to the effects of transient variations in the regional crustal stress field or the resistance of faults [44] caused by the hydrodynamics of local aquifers. This would explain why the phenomenon remains localised and of relatively moderate amplitude.

CONCLUSION

No previous study has mentioned the seismic record in Chad. The earthquake that occurred unexpectedly in 2015 in the Wadi Fira region in the east of the country, the study of the seismicity of this region over a relatively long period (4 years before and 1 year after the earthquake) has given us a broad view of the seismic problems in Chad. The signals recorded during this period were processed and located for those with a magnitude greater than 2. The epicentre is located in a very rugged area of the Ouaddaï massif. This massif is fractured and eroded.

Satellite and topographic data, coupled with seismic data, has enabled us to highlight spectacular lineaments on the edge of SE-NW oriented mountain ranges passing through the south of the Tibesti massif. This great lineament is the succession of faults that can be observed locally from Algeria to Kenya. It corresponds to all the faults that have affected the Pan-African Mountain ranges. These faults can replay and give rise to isolated earthquakes.

However, the non-reproducible nature of the event shows that it was an isolated earthquake, the kind that occurs infrequently in stable continental regions. In fact, these stable regions outside the boundaries of tectonic plates are the site of relatively rare unexpected and enigmatic earthquakes that affect unprepared regions and therefore systematically cause damage. These earthquakes are triggered by transient, local disturbances in tectonic forces, rather than by the slow accumulation of these forces on persistent faults as in the case of plate boundaries. These disturbances may be of external origin, resulting for example from episodes of rapid erosion or hydrological variations in the subsoil, or even a surge of Precambrian magma. These various disturbances are sufficient to overcome the resistance of faults already close to rupture, which then release the elastic energy accumulated in the volume of the continental crust over several million years. We now know that it is possible to have an earthquake in an area that is supposed to be very stable. These results suggest that we should monitor the seismicity of this region and continue our research into its seismicity in the distant past.

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