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ORIGINAL PAPER

The recent seismicity of northern Algeria: the 2006–2020 catalogue

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Abstract
An accurate and complete seismic catalogue is fundamental for studying the temporal, spatial, and size distribution of earthquakes. It also aids in the review of hazard assessment studies and geodynamic processes. In this paper, we present a new Algerian Seismic Catalogue for 2006–2020, compiling the more complete and accurate seismic events recorded in the referenced period. This catalogue is issued from data collection of the new Algerian Digital Seismic Network composed of 80 digital stations mainly distributed in northern Algeria and one at Tamanrasset in the south. The resulting catalogue contains 4858 events that were declustered from a total of 9000 recorded ones by removing foreshocks, aftershocks, and mine blasts. The parametric catalogue includes the following information for each earthquake: date, origin time, geographical coordinates (longitude and latitude), magnitudes (Md, Mb or Mw), focal depth, intensity (I_0), and, for the strongest events, spectral source parameters and focal mechanisms. In contrast to previous catalogues, the current one is the most accurate of Algerian seismicity due to both digital data and modern locating methods. Indeed it is characterised by a remarkable improvement in the total number of events recorded with a completeness magnitude of Mc 2.5 and by the accuracy of earthquake parameters estimation. The seismicity distribution of the resulting catalogue reveals that two-thirds of the epicentres are clustered in the central and eastern Algeria. In comparison, the western region remains quieter with a few events recorded. The recent activity reported in the catalogue enables the delineation of previously poorly known seismogenic zones such as the Medea basin, the Babors region, the North Constantine–Mila basin, or N–S named "the 4°50 shear zone" of the Hoggar shield. For the first time, the catalogue documents an induced earthquake during the 2007 Mila seismic crisis. The recently collected seismic data allow us to distinguish the epicentral zones of several historical events from previous catalogues.

Keywords Algeria · Instrumental earthquake catalogue · ADSN seismic network · Earthquakes · Seismic parameters · Seismogenic zones

1 Introduction

One of the main challenges for seismic risk assessment in earthquake-prone countries like Algeria is to use a complete, up-to-date, and reliable catalogue for better seismic hazard assessment. To achieve this goal, collecting as much historical and instrumental seismic data as possible is necessary to build a more realistic picture of the country's seismicity. Due to the existence of archives dating back to antiquity, countries such as Italy (Boschi et al. 2000) or Greece (Mallet 1855) have the most detailed catalogues in the Mediterranean region up to (2000 B.C).

Several attempts have been made in Algeria to compile disparate historical data on earthquakes and their parameters (Harbi et al. 2019 and references therein). As a result, various catalogues have been published and improved since the 1900s (Rothé 1950; Grandjean 1954). On the one hand, these catalogues suffer from the incompleteness and inaccuracy of their seismic data because of exogenous or endogenous causes. Among them, the different historical occupations of Algeria (Romans, Vandals, Turks) make the collection of seismic and macroseismic seismic data a rather difficult task.

In Memoriam of Assia Harbi, a colleague and friend who devoted her life to enrich the historical seismicity of Algeria.

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On the other hand, few seismological stations were installed after the first station in 1910, resulting in the absence of significant events from the instrumental catalogues. Most of the time, this has necessitated the use of foreign stations to obtain information on local events, sometimes resulting in erroneous localizations.

The installation of the new ADSN (Algerian Digital Seismic Network) in 2006 (Yelles-Chaouche et al. 2013b) with several seismic stations that use modern acquisition technics, transmission and data analysis marks a significant progress in seismic monitoring in Algeria, in addition to the onset of advanced seismological studies. Following the daily survey of seismic activity, the ADSN constitutes the first rapid alert system for authorities to a quick response in case of an earthquake emergency.

The main aim of this paper is to present Algeria's new seismic catalogue for the 2006–2020 period according to the following outlines:

- We focus on data processing and event parameter determination,
- We identify the network performance and limitations in light of the current operating number of stations,
- We explain data analysis at various stages, from the alert phase to the final data output parameter file,
- We reveal the catalogue template (see annex),
- We present the key outcomes using either general (Fig. 1) or regional maps. Attention is paid to the different seismogenic zones in northern Algeria,
- Finally, we discuss the evolution of the knowledge regarding the location of historical events based on the catalogue's most recent data.

2 Seismotectonic setting

Seismic activity in Algeria is related to the oblique convergence between the African and Eurasian main plates, which began in the early Cenozoic and led to the Alpine orogeny, represented by the Tellian thrust sheet belts in the north and the Atlasic belts in the south (Fig. 2). One of the most significant post-collision effects is the reorganisation of the Tethys ocean through several subduction zones, as well as the fragmentation of the AlKaPeCa block (Bouillin 1986; Schettino and Turco 2006). An extensional phase occurred during the Middle Miocene, leading to the opening of several intramountain basins known as post thrust sheet basins. The northern limit of the Tell belt region has undergone tectonic inversion since the Pleistocene period (Strzerzynski et al. 2010), demonstrating active compressional tectonics as evidenced by the present-day compressive stress field regime (Serpelloni et al. 2007). According

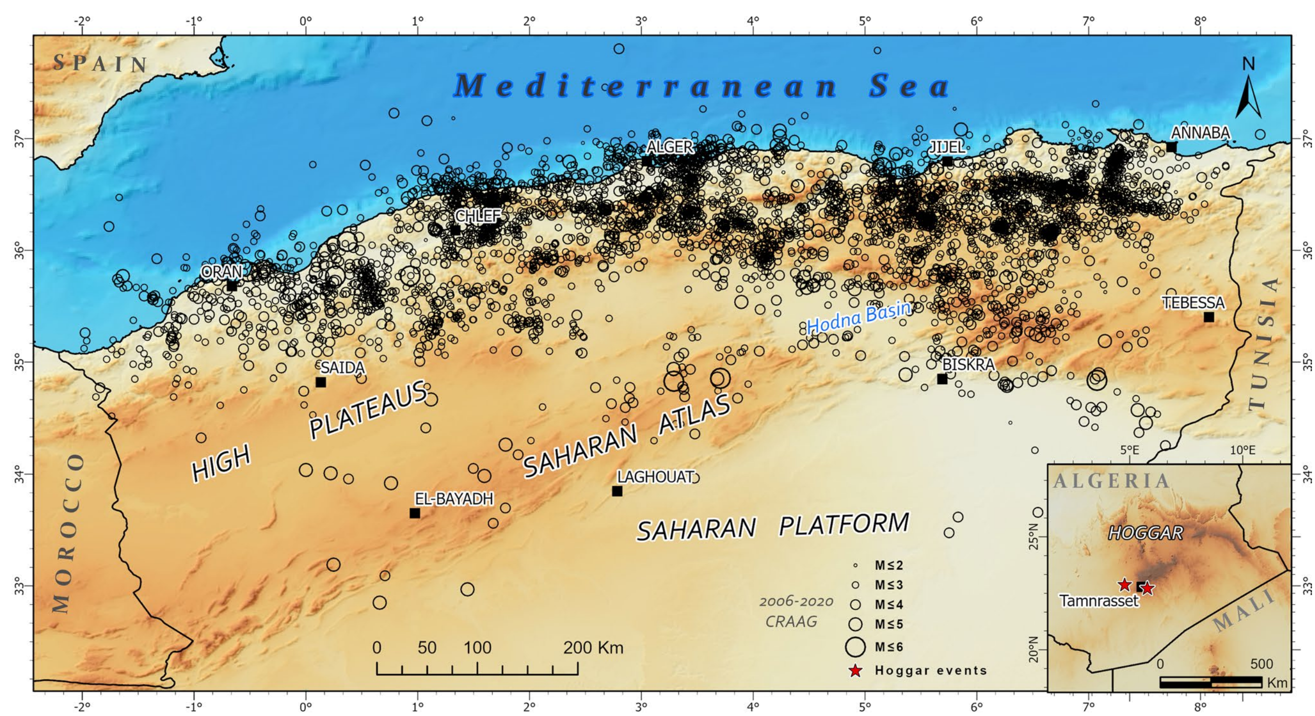


Fig. 1 The distribution of seismicity in northern Algeria from 2006 to 2020. The events recorded by the Algerian Digital Seismic Network (ADSN)are depicted in black circles. Two events in the Hoggar region, near Tamanrasset city, are depicted in the inset: one in 2010 and one in 2013

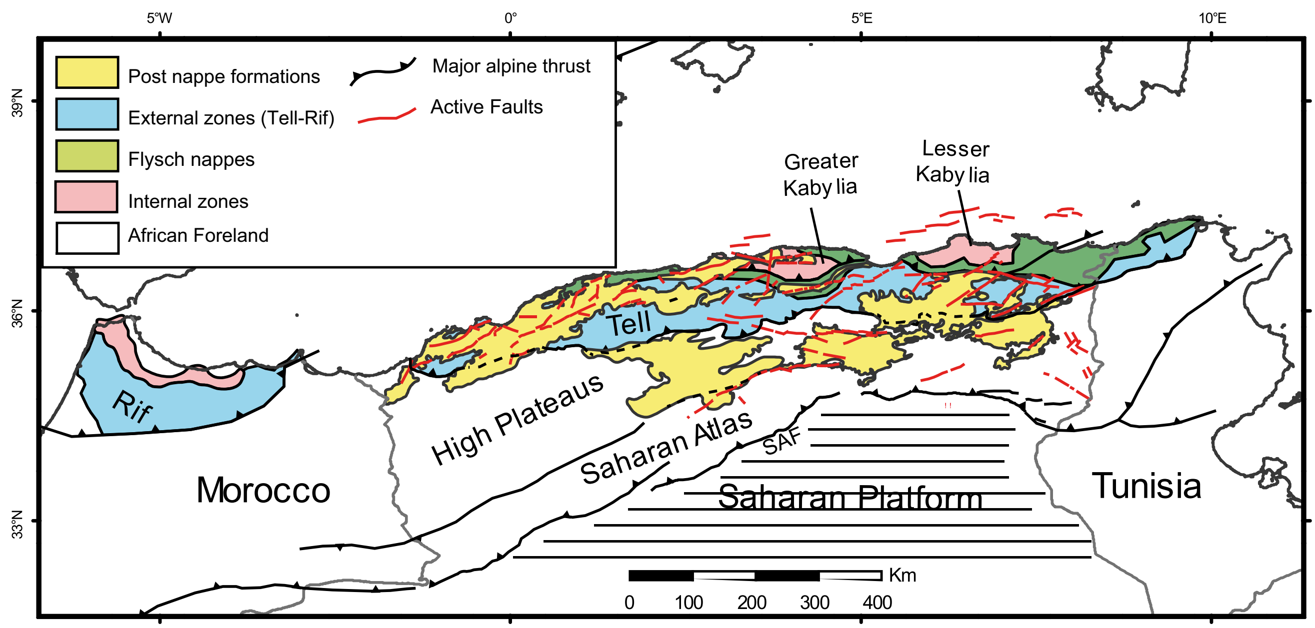


Fig. 2 The Tectonic Map of Northern Algeria indicates the major geological domains, with active faults represented by red lines

to plate kinematics studies, the collision velocity rate in the western Mediterranean region north of Algeria is estimated at 0.5 cm/year along the NNW–SSE direction (Stich et al. 2003; Nocquet 2012).

Recently, several marine surveys, such as the Maradja and Spiral projects (Yelles-Chaouche et al. 2010), have been conducted to better understand the deep and shallow structures of the Algerian coast and the reactivation processes. They resulted in imagining the crust thickness, mapping the active or potential active faults, and most importantly, revealing one of the rare examples of passive margins undergoing inversion and possibly incipient to future subduction (Hamai et al. 2015).

The current active deformation is primarily concentrated in northern Algeria. Onshore, it manifests as a network of active faults (Meghraoui 1988). This is coherent with the kinematic model based on transpression, with shortening accommodated by clockwise block rotations (Meghraoui and Pondrelli 2012). From west to east, the architecture of active faults formed as *en echelon* thrust folds and conjugate strike-slip faults, dominated by NW–SE to E–W right-lateral strike-slip faults and NE–SW left-lateral range-front thrust faults that cut the Tell. Recent analysed earthquakes on the E–W Mcid Aïcha-Debbagh Fault in the eastern part indicated the reorientation of the principal compressive stress axis σ1 from east to west, from NNW–SSE (N 335° E) to N–S (N 355° E), respectively (Buforn et al. 2004; Bezzeghoud et al. 2014; Ousadou et al. 2014; Abacha 2015; Bendjama et al. 2021). Active faults are mostly concentrated along the basin borders in several Tellian Neogene basins, such as Chelif, Mitidja, and Constantine basins (Yelles-Chaouche et al. 2006). Recent offshore studies (Déverchère et al. 2005; Domzig 2006; Kherroubi et al. 2009; Leprêtre et al. 2013; Bouyahiaoui et al. 2015; Mihoubi et al. 2014; Aïdi et al. 2018) show that the deformation in the central and eastern parts is expressed by a blind thrust system, located under the margin at the slope toe that goes toward the surface in a mainly NE–SW direction. However, the offshore deformation in the western part is related to the deformation in the Alboran domain caused by the Subduction-Transform-Edge-Propagator (STEP) fault system.

To contribute to the seismic risk assessment. Several previous hazard analyses employed the available catalogues to characterise potentially earthquake shaking using probabilistic (Hamdache 1998) and deterministic (Aoudia et al. 2000) methods. Those studies divided northern Algeria into separate seismogenic zones. The Cheliff region, damaged by the October 10, 1980 (Mw 7.3) El Asnam destructive earthquake, and the Algiers region, affected by the May 21, 2003 (Mw 6.8) Boumerdes destructive earthquake, maintain the highest values in terms of peak ground acceleration (PGA). Nevertheless, a constant hazard assessment update is required based on the catalogue evolution.

3 Historical catalogues

Although strong historical seismic events were mentioned and reported in documents during the Roman and Turkish periods, scientific interest in Algerian historical seismicity began primarily during the French occupation in the nineteenth century. Indeed, numerous scientific publications

(Perrey 1847–1870; Aucapitaine 1856; Chesneau 1892; Cochard 1867) began to be released on several seismic events, including their effects on villages and cities.

The first seismic catalogues in Algeria appeared in the twentieth century. They were compiled progressively by several scientists affiliated with the *Institut de Physique du Globe de Strasbourg* (IPGS) and the *Institut de Météorologie et de Physique du Globe d'Alger* (IMPGA). (Hée 1950; Rothé 1950; Grandjean 1954; Benhallou et al. 1971; Roussel 1973) have reported the most significant Algerian earthquakes progressively since 1716, the date of the main Algiers earthquake. Seismological parameters such as the geographical location, magnitude, and Intensity value have begun to characterise seismic events in these recent catalogues.

In the 1980s, the catalogues of (Benhallou 1985) and (Ambraseys and Vogt 1988) improved the previous documents by adding newly discovered events or providing additional information such as isoseismal maps of historical events as the Djidjelli event of 1856. More recent catalogues later supplemented their work (Mokrane et al. 1994; Benouar 1994; Harbi et al. 2007a, b, 2017a; b; Harbi and Maouche 2009).

Harbi was the one who made greatly enriched historical seismicity since its first publication on the subject (1999). Step by step, through her work, many historical earthquakes were discovered and added to the listing of the catalogue. For instance, her investigations in the Roman period revealed the impact of many earthquakes on archeological monuments (Ferdi and Harbi 2014). Her most significant contribution, however, was a thorough examination of the French archives, which allowed her to discover a significant number of new events and revisit others, such as the event of 1856 in Djidjelli (eastern Algeria). The collection of a large amount of information on the effects of these events contributes to the creation of a macroseismic database (Harbi et al. 2015).

Among the devastating seismic events reported in these catalogues are the following: the 1716 Algiers event with approximately 20,000 human losses, the 1790 Oran event with an associated moderate tsunami observed on the Spanish coast, the 1825 Blida event with approximately 7000 human casualties, the 1856 Djidjelli event with the destruction of the main city, and the 1981 Gouraya event associated with an important landslide (Maouche and Harbi 2008).

Nevertheless, it is crucial to outline that Laporte and Dupuis (2009) are the first to report the Negrine event (eastern Algeria) in 267 (A.D.), which is now regarded as the first known event in Algeria. The authors stated that the city of Negrine was severely damaged during the reign of Roman consul Paternus Arcelisaus. Another significant historical earthquake discovered recently (Yelles-Chaouche et al. 2009a) is the 419 (A.D.) Sitifis (now Sétif) earthquake reported by Saint Augustine, the famous Christian theologian from Hippone (now Annaba), which necessitates a particular attention to the seismic risk of an economic city like Sétif. These significant seismic events revealed by the catalogues highlight the possibility of large-scale events occurring in northern Algeria, resulting in the deaths of thousands of people and the destruction of cities and villages (Yelles-Chaouche et al. 2017a).

For historical events, the intensity remains the most relevant parameter based on human perception of the shaking level and the consequences of the earthquake on buildings, infrastructures, lifelines and the natural environment. Isoseismal maps derived from intensity values reveal the zone of maximum damage (the Pleistoseist zone) as well as the gradual attenuation of the earthquake effects. Several authors as Roussel (1973); Benhallou (1985); Bezzeghoud et al. (1996); Ayadi and Bezzeghoud (2015) have proposed numerous intensity maps associated with the catalogues to describe the regions of Maximum Intensities for northern Algeria. In addition to MOI maps, a Maximum Calculated Intensity (MCI) map has been proposed as a contribution to seismic hazard assessment from a compilation of the aseismic catalogue database for the period 1716–2000 (1458 events) (Boughacha et al. 2004).

The re-establishment of the seismological network in 1998 enabled (Yelles-Chaouche et al. 2002, 2007) and (Hamdache et al. 2010) to extend previous catalogues to the years 1992–2008. At the moment, the Algerian seismic catalogue is continuously updated with new events and discoveries from both historical and instrumental periods.

4 Development of the Algerian seismological network

The era of instrumental seismology in Algeria began in 1910, with the installation of the first seismological station in Algiers, specifically at the Bouzareah Observatory (Roussel 1973). It was equipped with a mechanical seismograph made by Bosch-Mainka. Following that, other seismic stations equipped with short-period Grenet–Coulomb seismographs were installed in several cities in northern Algeria, such as Tlemcen (western Algeria), Sétif (eastern Algeria) in 1958, and Relizane (western Algeria) in 1955. Five years after the El Asnam earthquake, in 1985, the CRAAG received financial assistance to renovate and modernise the seismic monitoring system. In 1990, a new seismological network (radio-link stations technology) of 32 telemetry stations was installed, which was divided into four sub-regional networks (Algiers–Oran–Chelif–Constantine) (Bezzeghoud et al. 1994). Unfortunately, the network lasted one year before being shut down due to Algeria's political issues in the nineties. The Algerian network was reactivated in 1998 to record the seismic activity of the country, marked by daily events.

Following the Boumerdes event on May 21, 2003, the public authorities provided the necessary funds for the network digitalization, which was executed in 2006 with the purchase of 50 new digital stations (10 BroadBand and 40 short-period stations). They were mostly installed in the country's northern part, which is seismically the most active and has the highest population density (Fig. 3). A Very BroadBand station was dedicated to the Tamanrasset Observatory, 2000 km south of Algiers, to monitor the Hoggar seismicity, where surprisingly, a significant event (Mw 4.5) shook Tamanrasset's main city on February 14, 2013.

The quality of recordings from each seismic station is used to evaluate the ADSN's performance (Yelles-Chaouche et al. 2013b). It is well recognised that the signal and noise characteristics of any new seismic network's sites will govern its ability to detect earthquakes and record representative event waveforms. The geographic region of interest, seismo-geological conditions, accessibility, seismic noise sources in the region evaluated through PSD, data transmission and power considerations, land ownership and future land use issues, and climatic conditions are all factors considered during the installation of ADSN stations.The quality of broadband data from the Algerian network is currently being continuously monitored using the "PQLX" software (McNamara et al. 2009), which calculates PDFs (probability density function) and PSDs (power spectral density) of the recordings and edits weekly, monthly, and annual reports.

5 Data acquisition and processing

The seismic events selected in this catalogue are issued from the ADSN network and represent the daily activity recorded in northern Algeria between 2006 and 2020. Portable stations are sometimes deployed for a limited time following strong events to densify the network and record aftershock activity.

Algerian seismic activity is monitored in two stages. The first consists of an alert phase via automatic data processing, which includes P-wave detection, event localization, and determination of the duration magnitude (Md) or body wave magnitude (mb). The number of stations involved in the detection of the event is a critical issue for the quality of the alert process. As a result, at least five stations are required to validate the detection of microseismic events.

The second step is to review the first alert phase again with a more standard analytical review of the data. We then proceed as follows: First, we store all data from the same event in a single database in the same format (e.g. "SAC"). Second, we use software such as MSDP, Antelope, SAC, and SEISAN for seismograms phase picking. The event is then localised using either a linear calculation method using

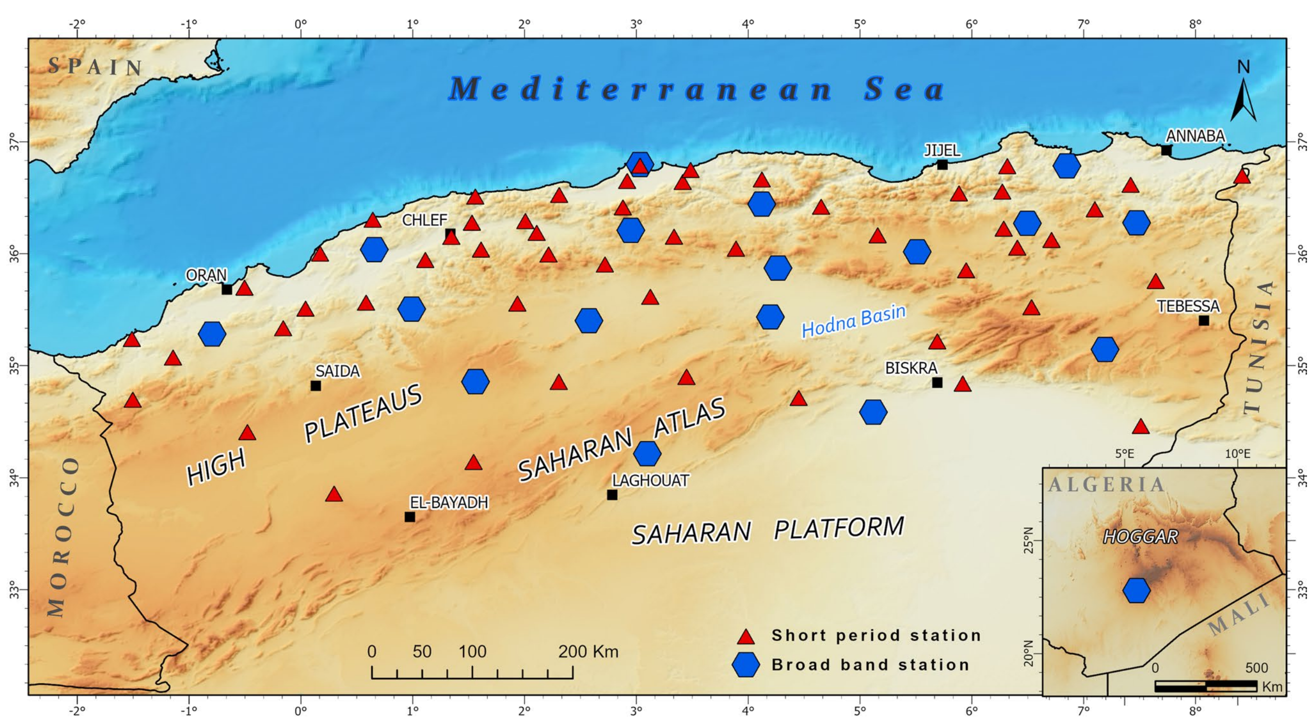


Fig. 3 Algerian Digital Seismic Network (ADSN): the red dots represent BroadBand (BB) stations, while the blue triangles represent short-period (SP) stations. The broadband station installed in the Tamanrasset Observatory is featured in the inset

the HYPOINVERSE program (Klein 2002) or a nonlinear calculation method using the NonLinLoc program (Lomax 2017).

To build a reliable 1D P-wave local velocity model, we use the VELEST program, an iterative 1D inversion algorithm (Kissling et al. 1994), and we calculate the Vp/Vs ratio by the modified Wadati method (Chatelain 1978). Following this first step, events with a root-mean-square (RMS) travel time residual of less than 0.30 s, location uncertainties in the horizontal (ERH) and vertical (ERZ) direction of less than 2 km, and an azimuthal gap of less than 180° are considered best-located events and are included in the final dataset. To refine the relative locations of events, we relocate them using the HypoDD algorithm of Waldhauser and Ellsworth (2000).

Separating an earthquake catalogue into foreshocks, mainshocks, and aftershocks, is widely used in seismology, particularly for seismic hazard assessment and earthquake prediction models (Van Stiphout et al. 2012). Independent earthquakes are assumed to be caused mainly by tectonic loading, while dependent earthquakes are generated by mechanical processes controlled by previous earthquakes. Foreshocks and aftershocks are both temporally and spatially dependent on the mainshock. Earthquake catalogues are often declustered by removing dependent earthquakes. The declustering process aims to study a given area using only the mainshocks because they represent its seismic activity. Over the years, several declustering algorithms have been proposed (Van Stiphout et al. 2012). Gardner and Knopoff's (1974) method is used because it is simple to apply and strongly correlates with the Poissonian model. Gardner and Knopoff (1974) assume that subsequent analyses such as prediction models, the study of earthquake spatio-temporal behaviour, and probabilistic hazard analysis cannot be properly performed unless the catalogue is separated from non-Poissonian random events.

Between 2006 and 2020, the ADSN network located over 9000 events, to which we applied the Gardner and Knopoff (1974) clustering method implemented in Stefan Wiemer's ZMAP package (Wiemer 2001) for MATLAB. We removed 4144 events (forming 1095 clusters) from the catalogue, leaving only 4858 events (about 54% of the initial catalogue) representing independent earthquakes.

The focal mechanisms of the different seismic sequences were calculated using the polarities of the first P-wave motion (we retain events with a minimum of seven polarities). We use several programs, such as SPHERA (Rivera and Cisternas 1990), SEISAN's FOCMEC, and FPFIT (Snoke 1984). In addition, we used a waveform modelling technique developed by (Yagi and Nishimura 2011) to independently estimate the focal mechanism for mainshocks and strong aftershocks. We have completely automated since 2010 the inversion operation by integrating the code into Matlab. Several routines have been implemented for the pre-processing and analysis of the data. The code calculates the seismic moment and adjusts the depth of the earthquake. Due to the low number of broadband stations at the time of their occurrence, some focal mechanisms are shown in black (Fig. 4 and Table 1). For these events, the focal mechanisms were obtained from international agencies.

To determine the current stress tensor parameters, we used the Win-Tensor program (Delvaux 2012) and the GRIDSIMSTRESS algorithm (Delouis et al. 2002; Beldjoudi et al. 2009). The results were used to investigate the spatial variation of the principal stress axes.

We also estimated the source parameters of strong seismic events using MATLAB code developed by Abacha et al. (2019) and based on a circular seismic source model (Brune 1970, 1971).

In addition to determining the physical parameters of earthquakes, we have conducted macroseismic studies to highlight spatial variations in the seismic shaking level (local effects, decay with distance); to measure historical earthquakes (evaluate their Intensities); and to inform authorities about the earthquake field effects (natural disaster procedure). Furthermore, macroseismic intensity information is an important decision-support tool for government officials and engineers who establish building seismic standards, etc. For the main events, we conducted a standard macroseismic survey surrounding the epicentral regions. We also used social media networks to better constrain the affected zones before assessing the intensity value using the EMS Scale 98.

6 The 2006–2020 catalogue: format and spatio-temporal analysis

In terms of input data, this new version of the Algerian catalogue for 2006–2020, referred to as the 2006–2020 catalogue, represents significant progress over the previously published ones. All digital data is obtained from the ADSN network, and the preferred dataset is chosen based on the following criteria. The root-mean-square (RMS) error is 0.3 s, the horizontal (ERH) error is 2 km, and the vertical (EHZ) error is 2 km. Thus, the 2006–2020 catalogue includes 4858 events, most located in Algeria's northern onshore and offshore regions.

As per the standard catalogues, the 2006–2020 catalogue, provides the following information for each earthquake: Date, Origin Time, Geographic Coordinates (Lat, Long), Intensity (I_0), Magnitudes (Md, Mb, or Mw), Depth, the root-mean-square (RMS), error in the horizontal direction (ERH), error in the vertical direction (ERZ), the region of the earthquake location, and nodal planes (Strike, Dip, Rake) for moderate to strong events (annex 2, Fig. 4).

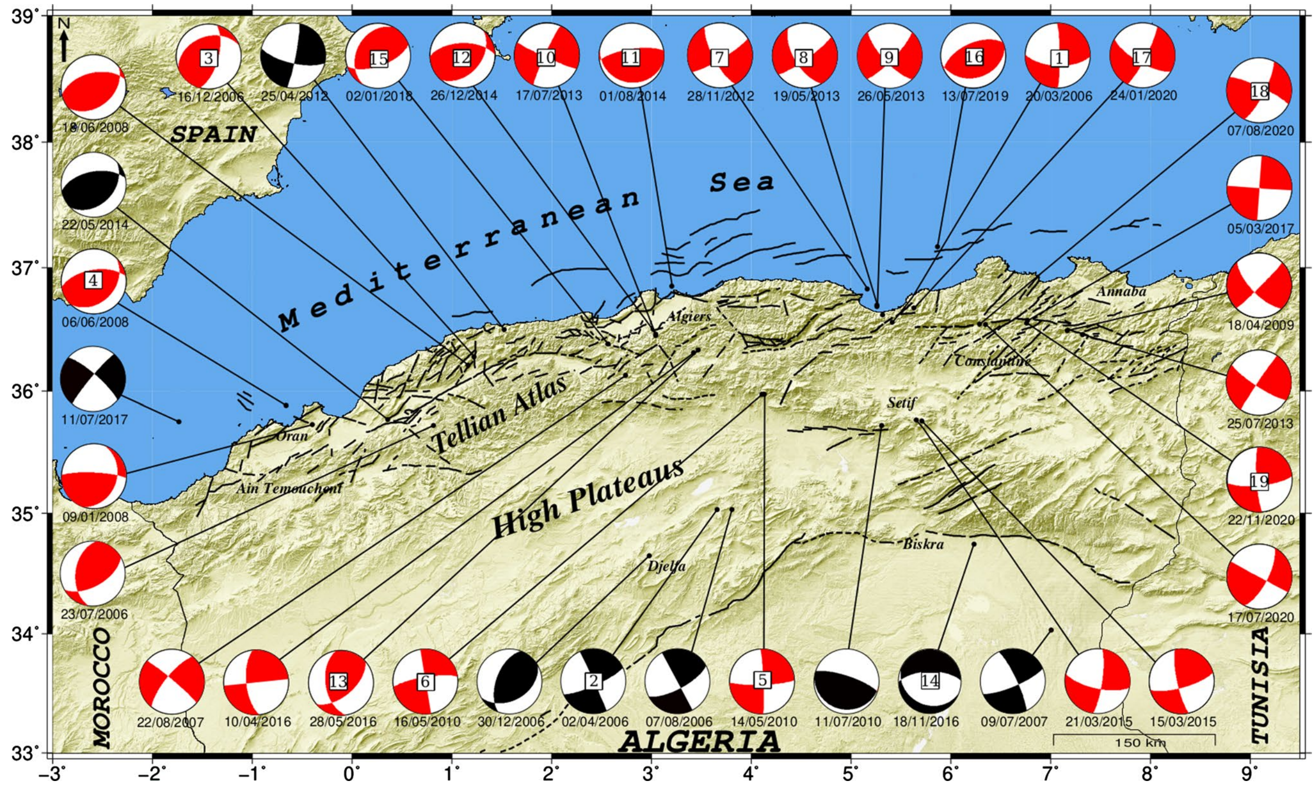


Fig. 4 A map portraying the focal mechanisms of main earthquakes (Mw > 5.0) from 2006 to 2020. The black lines represent the main active structures from previous studies. The focal mechanisms in red are calculated at CRAAG. The focal mechanisms in black are from international agencies. The FM (Focal Mechanism) number are reported for the main events

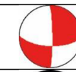
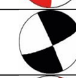
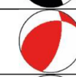
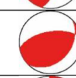
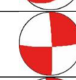
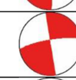
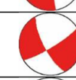
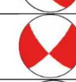
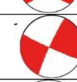
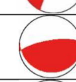
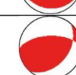
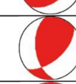
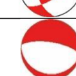
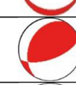
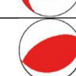
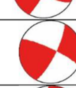
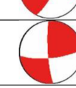
We display the total number of recorded events (9000) in blue and the declustred events (4856) in pink on the histogram in (Fig. 5), as well as the cumulative events per year. We observed an increase in events following the installation of the ADSN network in 2007, compared to the 2006 catalogue baseline year, with a peak of 591 recorded events in 2011. The total number of events reached 531 in 2010, the year of the Beni-Ilmane seismic sequence occurrence. With a total of 146 events, activity fell to its lowest point in 2019. The total number of events recorded over the years shows variations, indicating that stress relaxation in the crust is not uniform each year.

During this 15-year period, and although the year 2021 is not yet included in this catalogue that stops at the end of 2020, we point out that the maximum magnitude recorded is Mw 6.0 of the most recent event in Bejaia on March 18, 2021 (Yelles-Chaouche et al. 2021b). We recorded 30 events with Md ≥ 5 affecting various regions of northern Algeria, representing 0.33% of the total number (Fig. 6a and Table 1). They are mostly found in the central-eastern part of northern Algeria. The strongest events recorded in the Oran region for the western part are in the Mleta (lower Chelif) basin in January 2008 (Mw 4.7) and in the offshore par in June 2008 (Mw 5.4) (Benfedda et al. 2020). The event depth distribution in Fig. 6b shows that the highest density of hypocenters is between 0 and 10 km, with an average of 7 km. This is consistent with a process of surface crustal deformation related to the current convergence of the two main plates. There have been no intermediate or deep events detected.

In contrast to previous catalogues, this one includes primarily low-magnitude events, which now account for the majority of activity recorded in northern Algeria. More than two-thirds of the recorded seismic events have a magnitude of 2 ≤ Md ≤ 3 (Fig. 6a). Nonetheless, given the current network coverage, the magnitude threshold has been reduced to 2.5 (Figs. 7 and 8a) avoiding the need to resort to foreign catalogues as the Spanish catalogue for the knowledge of the occurrence of some Algerian events as made in previous catalogues. On the other hand, event location accuracy has greatly improved, with a maximum level of confidence obtained with 5 or 6 stations.

We performed a power-law distribution analysis on the data collected in the catalogue that was characterised by the size of exponents in both domains of seismic events (Gutemberg–Richter law, exponent b). The computed Gutemberg–Richter law (Fig. 8) offers a b-value of 0.8 for the overall declustred catalogue and a b-value of 0.9 for

Table 1 The main earthquakes from 2006 to 2020, along with associated parameters and focal solutions

Focal solution number in Figure 4 (FM)	Date	Lon	Lat	M_w	Plan 1			Plan2			Focal solutions
					Strike	Dip	Rake	Strike	Dip	Rake	
1	20/03/2006 Lalaam (Bejaia)	5.41	36.56	5.2	92	64	-174	359.4	84.6	-26.1	
2	02/04/2006 Djelfa	3.66	35.03	5.1	66	79	-178	335.6	88	-11	
3	16/12/2006 Chlef	1.22	36.28	5.0	249	38	137	15.3	65.2	60.3	
4	06/06/2008 Oran	-0.64	36.06	5.5	45	35	60	260	60.2	109.3	
5	14/05/2010 Beni Ilmane	4.13	35.97	5.2	88.1	81.3	-175.8	357.3	85.1	-8.7	
6	16/05/2010 Beni Ilmane	4.11	35.98	5.0	170.9	89.8	-11.6	260.9	78.8	-179.8	
7	28/11/2012 Bejaia	5.16	36.83	5.1	152	73.0	-170	59	80.4	-17.2	
8	19/05/2013 Bejaia	5.26	36.70	5.3	149	63.0	-170	54.4	81.1	-27.4	
9	26/05/2013 Bejaia	5.26	36.69	5.0	137.2	73.4	-168.3	43.7	78.8	-17.3	
10	17/07/2013 Hamma Melouan	3.04	36.45	5.0	114.2	85.7	174.6	204.6	84.6	4.3	
11	01/08/2014 Algiers	3.21	36.85	5.3	261.2	73.6	84.2	101	17.4	109	
12	26/12/2014 Hammam Melouan	3.04	36.46	5.1	268.5	58.7	119.5	41.1	42	51	
13	28/05/2016 Mihoub	3.47	36.34	5.4	171	51	44	171	51	44	
14	18/11/2016 Biskra	6.27	34.82	5.2	96.1	20	92.7	279	70	-89	
15	02/01/2018 Oued Djer	2.56	36.38	5.0	207	34	52	70.3	63.9	112.6	
16	13/07/2019 Jijel	5.82	37.16	5.0	75.2	32.3	98.3	245.4	58.2	84.8	
17	24/01/2020 El Aouna Jijel	5.63	36.68	5.0	120	72.0	-171	27.2	81.4	-18.2	
18	07/08/2020 Mila	6.29	36.55	5.0	295	80.9	166.6	27.2	76.8	9.4	
19	22/11/2020 Mila	6.76	36.55	5.3	176	82	15	83.9	75.1	171.7	

the raw data. Hamdache et al. (2010) estimated a *b*-value of 0.9 for 1920–2000. The *b*-values ranging from 0.5 to 1.5 are commonly influenced by two factors: rock density and normal effective stress. A high *b*-value indicates a fractured zone suitable for low-magnitude events' triggering. A low *b*-value, on the other hand, favours high-magnitude events. The estimated *b*-value may indicate that tectonic loading forces dominate the produced catalogue. As for the *b*-values of seismogenic sources, Pelaez et al. (2005) estimated the *b*-values for the separate seismic zones of Northern Algeria. Abacha (2015) and Hamidatou et al. (2019) stated that the *b*-value for various seismogenic zones was an indicator factor for the fracturing process in several seismogenic zones in northeastern Algeria, where most recently (Abacha et al. 2022) evaluated *b*-values changing between 0.9 and 1.7. Specific studies on seismic sequences have also been carried out, revealing the triggering process for each case. Fluid-driven triggering

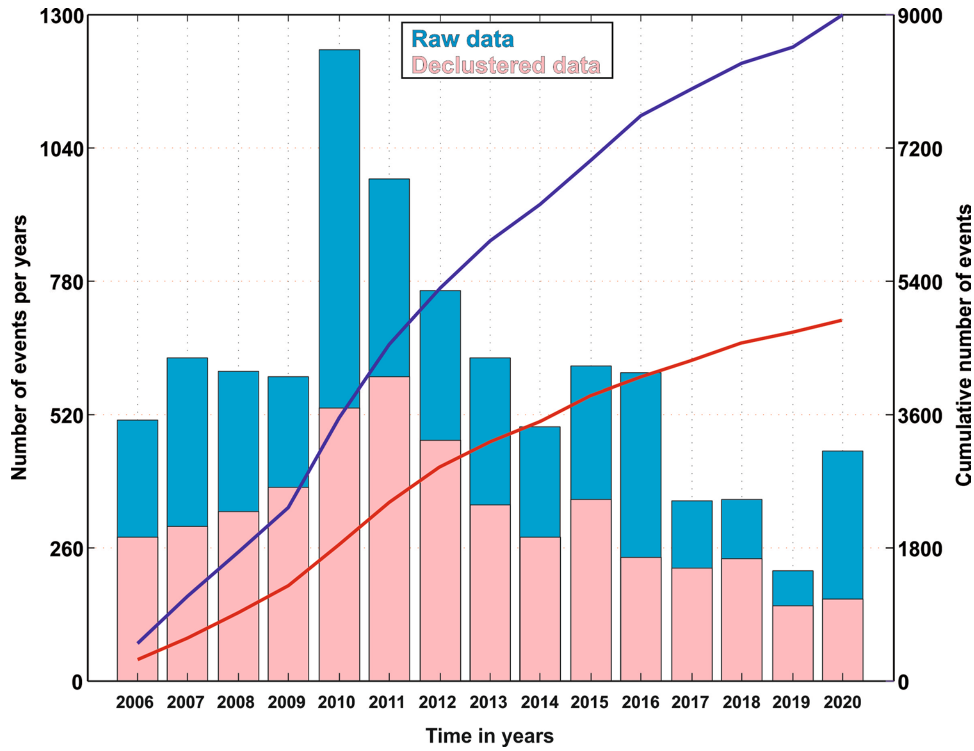


Fig. 5 A histogram of the number of events per year from 2006 to 2020. The total number of events before declustering is represented by the blue diagram. The pink diagrams illustrate the events that occurred after declustering. The blue line represents the cumulative number of events before declustering, and the red line represents the cumulative number of events after declustering

was established in the 2007 Mila seismic crisis (Semmane et al. 2012). However, the 2010 Beni-Ilmane seismic sequence was forced by tectonic loading (Hamdache et al. 2017 and Abacha et al. 2019).

Among the lessons of the 2006–2020 catalogue, we discovered for the first time several seismic sequences with a rupture process marked by many moderate events of magnitude 5, such as the sequence Beni-Ilmane in 2010 (Yelles-Chaouche et al. 2013a; Beldjoudi et al. 2016; Abacha and Yelles-Chaouche 2019), the sequence Bejaia-Babors in 2012–2013 (Boulahia et al. 2021), or the sequence of Hammam Melouane 2013–2016 (Yelles-Chaouche et al. 2017a, b). This implies in these cases that the total energy accumulated in the epicentral zone was released by several segments of the active fault system.

From the 2006–2020 period covered by this catalogue, we can see that the spatial repartition of the seismic activity fits with the previous map already established by the previous catalogues. However, this new catalogue identifies more accurately the epicentres locations in the seismogenic zones as for the offshore region: the Bejaia–Babors sequence (2012, 2013) (Boulahia et al. 2021), the Algiers event of August 1, 2014 (Yelles-Chaouche et al. 2018) and the Djidjelli event of 2019 (Yelles-Chaouche et al. 2021a).

In the continental part, seismicity of the different Neogene basins as the Mitidja basin, the Mila, or Guelma were also depicted on the identified faults system as the south Mitidja Fault system (Mohammedi et al. 2020), the Mcid Aïcha-Debbagh Fault (Bendjama et al. 2021).

Around the Greater and Lesser Kabylian blocks, knowledge of seismicity was enhanced through the important events in this area. For instance, seismic activity was evidenced on the Babors Transform Fault (Boulahia et al. 2021). In other major trends as the South Atlasic flexure, some significant events have been recorded.

Unprecedented events are also reported in the 2006–2020 catalogue. These are the cases of an induced event caused by the Mila crisis in 2007 (Semmane et al. 2012) and the earthquake located in the stable Saharan Platform. This later magnitude 3.9 earthquake occurred on January 7, 2018, at 8:25 a.m. near the city of El Oued, 20 km northwest of the small village of Djemaa (Saharan Platform). According to the CRAAG's field investigations, the event was strongly felt. As seen on the store's video surveillance system, the shaking level had an impact on the store's furniture. Unfortunately, there were no aftershocks associated with the mainshock to conduct a sound study.

We also report two small events in the Hoggar Shield in this catalogue. The first event occurred on May 21, 2010 (Md 3.9), near the village of Silet along the NS 4°50E shear zone. The second, a magnitude (Md 4.5) earthquake in February 2013, was the strongest ever recorded in the region and occurred 20 km southeast of Tamanrasset (Fig. 1, inset).

The inversion of focal mechanisms observed during the catalogue period confirmed that northern Algeria is subjected to a compressive stress regime as a result of the convergence of the African and European plates. Stress tensor parameters help to refine the deformation process

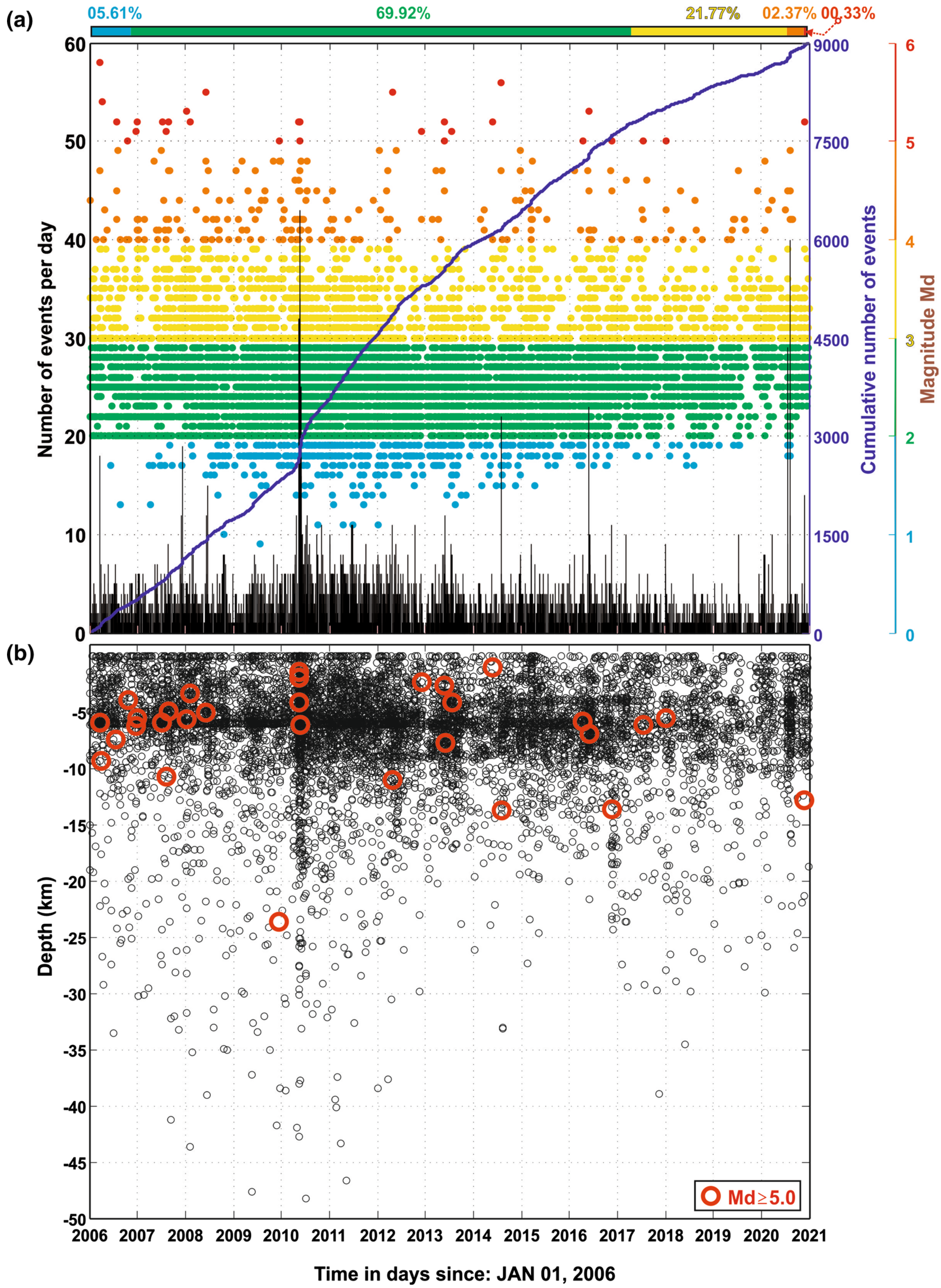


Fig. 6 **a** The cumulative number of events and Md per year for 2006–2020. Dots are coloured according to the magnitude of the events, ranging from blue (Md < 2) to red (Md ≥ 5). **b** The raw data's temporal evolution of the hypocenter depth. The events with a magnitude of 5 are represented by dots in a circle

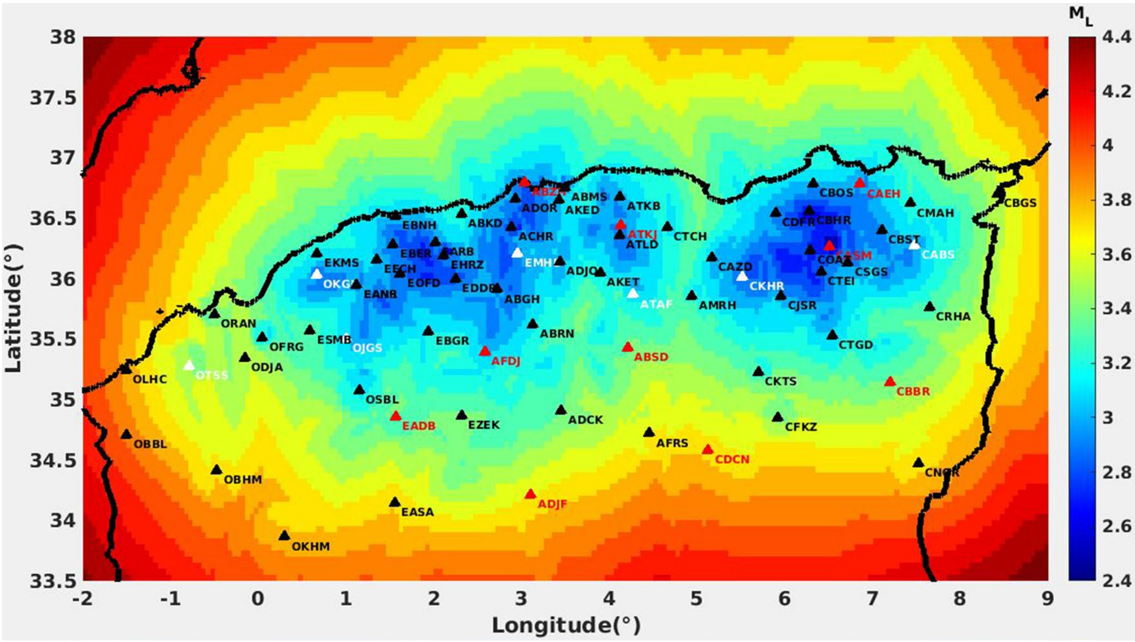


Fig. 7 The map below displays the lowest magnitude measured by the ADSN Network using a minimum of 5 stations. The Magnitude Scale is on the right

in seismically prone areas like the Algerian margin, the Bay of Algiers, and the Jijel–Bejaia margin. The proposed tectonic model for explaining the deformation from offshore to the continental part reveals a reorientation of the stress tensor from NW–SE to N–S going from east to west

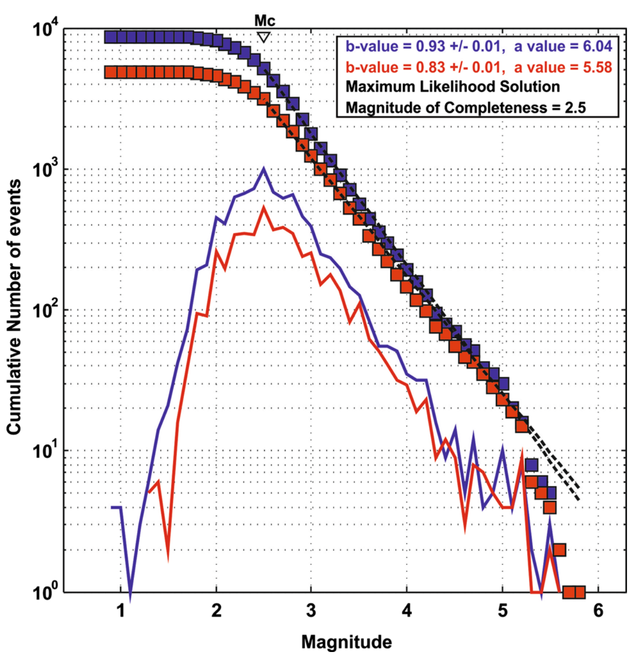


Fig. 8 Gutenberg's Richter law: determining the threshold magnitude. Blue represents raw data, and red represents declustred data

(Yelles-Chaouche et al. 2021a; Boulahia et al. 2021; Bendjama et al. 2021).

In the borders of the Lesser Kabylian Block, a clockwise rotation of the stress field, determined by the focal mechanisms (FMs) inversion of the main events and their aftershocks, has been observed (Fig. 9). The stress reorientation increases to the north, reaching a maximum (~ N–S orientation) in the coastal region (Bejaia–Jijel) and, to a lesser degree, along the GNC Fault, until becoming NW–SE in the block situated between the Aures Range and the GNC Fault (Bougrine et al. 2019; Yelles-Chaouche et al. 2021a; Boulahia et al. 2021; Bendjama et al. 2021) (Fig. 9).

The SHmax orientation appears more homogeneous in central and western Algeria than in eastern Algeria. Active faulting and seismicity indicate concentrated deformation in a narrow coastal band far (50–100 km offshore) characterised by a compressive stress regime. The FMSs of three moderate earthquakes, the 2006 Tadjena earthquake in the Chelif region (Beldjoudi et al. 2012), the 2014 Algiers earthquake in the offshore region (Yelles-Chaouche et al. 2018), and the 2016 Mihoub earthquake sequence in the Médéa region (Khelif et al. 2018), were recently used to calculate an NW–SE SHmax orientation. Comparing the average SHmax orientation and relative plate motion direction between the African and Eurasian plates confirmed the homogeneity of the stress in this part of Algeria (Soumaya et al. 2018).

Towards the south, along the South Atlasic flexure, the Biskra event of November 18, 2016 M: 5.2, which displays

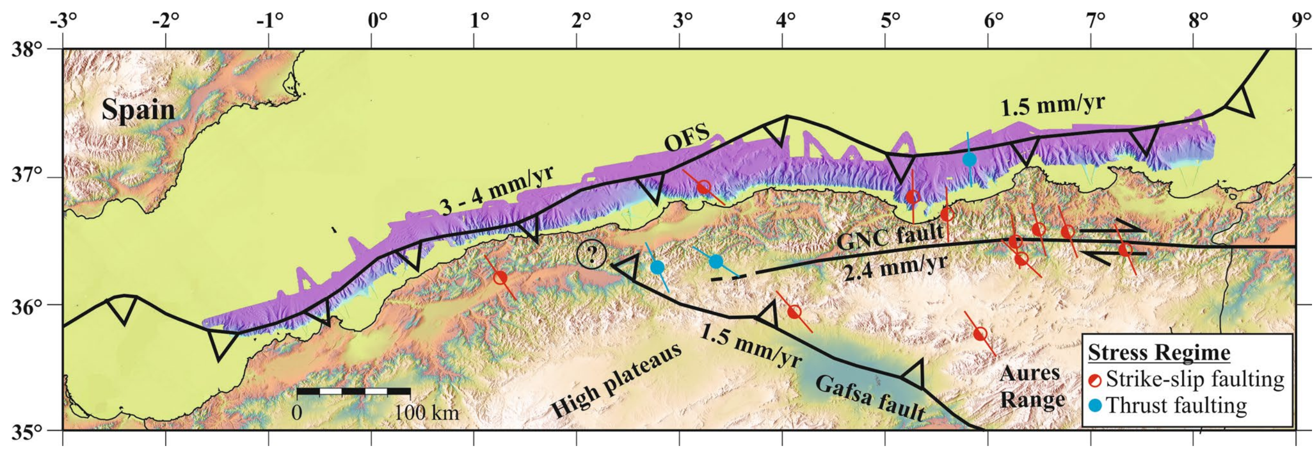


Fig. 9 Map of SHmax obtained from the inversion of the FMs of the main recent seismic events. The key structures are taken from Bougrine et al. (2019)

a normal focal mechanism, let us assume that local effects exist like the subsidence affecting the Saharan platform.

7 Seismogenic zones

In the following paragraphs, we present the recent seismicity for each seismic subregions of northern Algeria:

7.1 The eastern Algerian region

In this region, the seismicity that has been the most intense in this region over the last 15 years (Fig. 10), with a significant number of events (50% of the total number), affects a large area spanning the entire width of the Alpine belt, including the Atlasic domain. The occurrence has not been spatially homogeneous, as illustrated in Fig. 10, where areas of high seismicity are surrounded by land masses of lower activity.

- ***Around the Lesser Kabylian Block***

  The majority of the seismicity occurred along the borders of the Lesser Kabylia Block: (1) At the northern boundary, represented by the eastern Algerian margin, relatively quiet for more than 150 years since the 1856 Djidjelli earthquake (Yelles-Chaouche et al. 2009c; Harbi et al. 2011). The two 2019 Jijel (Mw 5, FM (Focal Mechanism) 16, Fig. 4) and 2014 Ziama (Mw: 4.1) earthquakes (Yelles-Chaouche et al. 2021a) were the first true instrumental signatures of seismic activity along the Jijel margin. They allow outlining the offshore active fault network as also a possible trigger for the 1856 event. In contrast, no seismic activity was detected east of the Jijel margin, from Collo to Annaba. Until now, it remains quiet, which is alarming for an active margin from a seismological standpoint; (2) At the western boundary, significant seismic activity has occurred in the Bay of Bejaia and the Babors area. For a long time, several authors suggested that the Kherrata reverse fault was the primary structure responsible for the region's seismic activity (Rothé 1950; Meghraoui 1988; Harbi et al. 1999, 2003). However, recent seismic activity (2006–2020) and associated focal mechanisms, in particular the Lalaam earthquake (Mw 5.2 in 2006, FM1, Fig. 4) (Beldjoudi et al. 2009), the Bejaia-Babors seismic sequences (FM, 7, 8, 9, Fig. 4) (Boulahia et al. 2021), and the 2020 El Aouana earthquake (FM17, Fig. 4) reveals a set of new right-lateral NW–SE *en echelon* faults. This strike-slip corridor connects the offshore thrust fault system to the Mcid Aïcha-Debbagh Fault; (3) The southern boundary of the Lesser Kabylia Block is underlined by the Mcid Aicha Debbagh Fault. Along this fault the present-day seismicity is intense but of low magnitudes, a feature that has paid attention of many seismologists due to the fault length of more than 80 km. The recent seismic events, which include the 2017 seismic sequences (Bendjama et al. 2021), the 2020 Mila earthquake sequence (Mw 4.9) marked by a destructive landslide of about 1000 houses (Benfedda et al. 2021) and the 2020 El Kantour earthquake (Mw 5, FM19, Fig. 4) show that this seismicity is generated by small segments along of Mcid Aïcha-Debbagh Fault; (4) at the eastern edge of the Lesser Kabylia Block we could depict easily an NS trending microseismicity at the western edge of the Annaba Basin between Filifla and Azzaba (Fig. 10). Seismicity east of this trend is quiet. Southward of this area, one can depict seismicity around the pull-apart Guelma basin.

- ***The El Hodna domain***

  Further to the southwest, significant activity occurred along the NW–SE Hodna chain, particularly the seismic

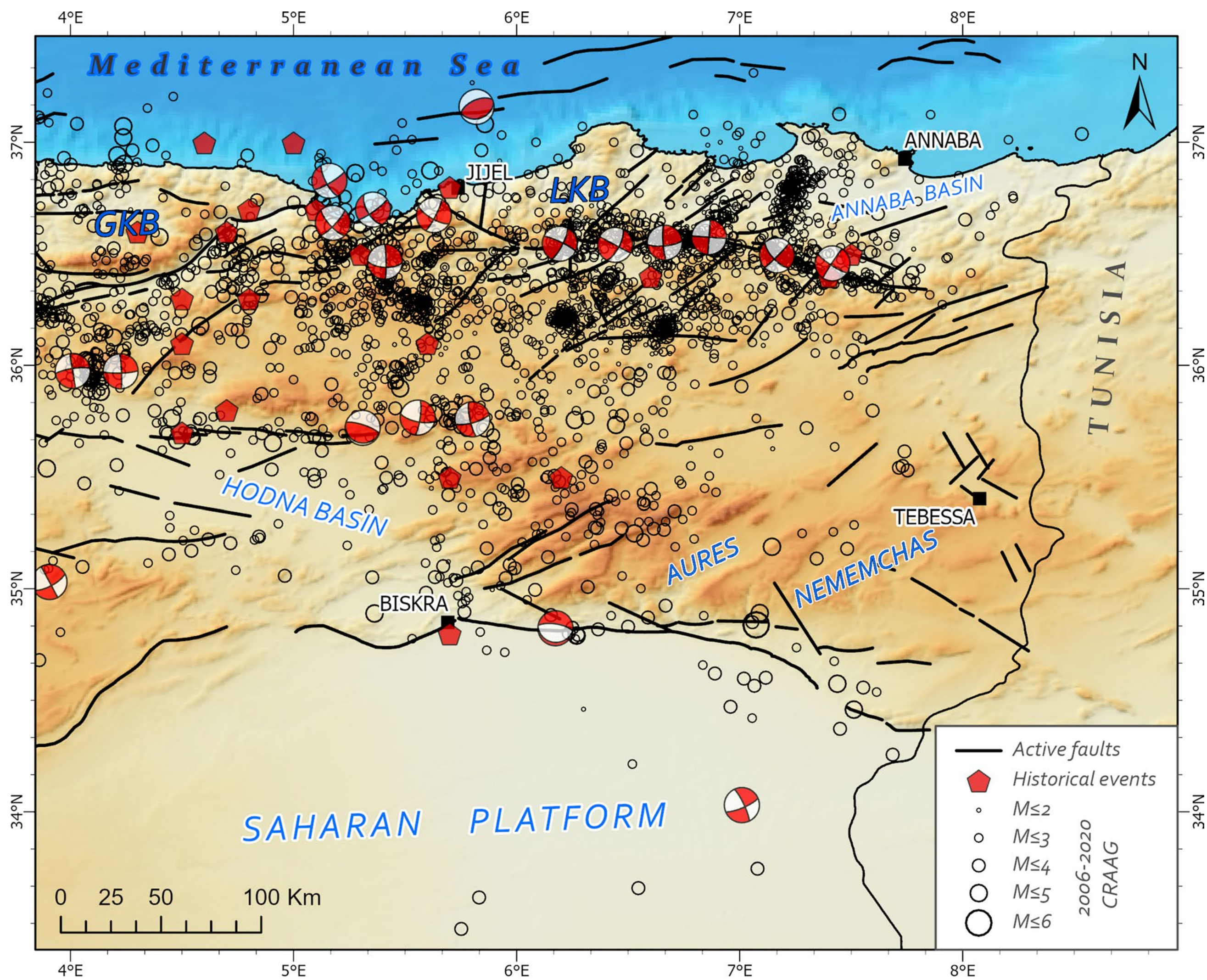


Fig. 10 The Eastern region's seismotectonic map. Seismic events are represented by black circles, active faults are represented by black lines, and historical events are represented by red circles. Beachballs are focal mechanisms

sequences of Beni-Ilmane in 2010 (Yelles-Chaouche et al. 2013a) and Ain Azel in 2015 (Fig. 4; Chami et al. 2019; Abacha and Yelles-Chaouche 2019; Abacha et al. 2022), demonstrating that the Tellian Atlas–High Plateau border region is an active seismogenic zone marked by moderate and plausible strong earthquakes. The occurrence of the 2015 and 2020 Ain Azel (southeast Setif) earthquake sequences on the same WNW–ESE Hodna lineament adds to evidence of Tellian Atlas south border seismic activity.

- ***The Atlasic domain***

As previously stated, the seismicity distribution in the northeastern part extends to the south, defining the seismically active territory's southern boundary. As a result, some moderate-sized earthquakes are reported in the current catalogue, such as the Biskara Mw 5.2 (FM 14) event in 2016 with a normal focal solution along the south Atlas, as well as events that occurred in the Saharan Platform near El Oued, culminating with the one on January 17, 2018.

7.2 The central Algerian region

In this region, seismicity between 2006 and 2020 occurred primarily along the borders of the Mitidja basin and the intramountain basins such as Medea and Beni-Slimane in the central part of Algeria (Boudiaf 1996, Fig. 11). According to the recent events reported in the catalogue, the inversion of the Algerian margin is marked by many epicentres, as demonstrated by the recent Mw 5.5 earthquake that struck the Algiers region in August 2014 (FM 11). This strongly felt event occurred offshore in a critical area of the Bay of Algiers, at the intersection of the Thenia Fault and the extension of the Sahel Fault, also confirms the gradual stress

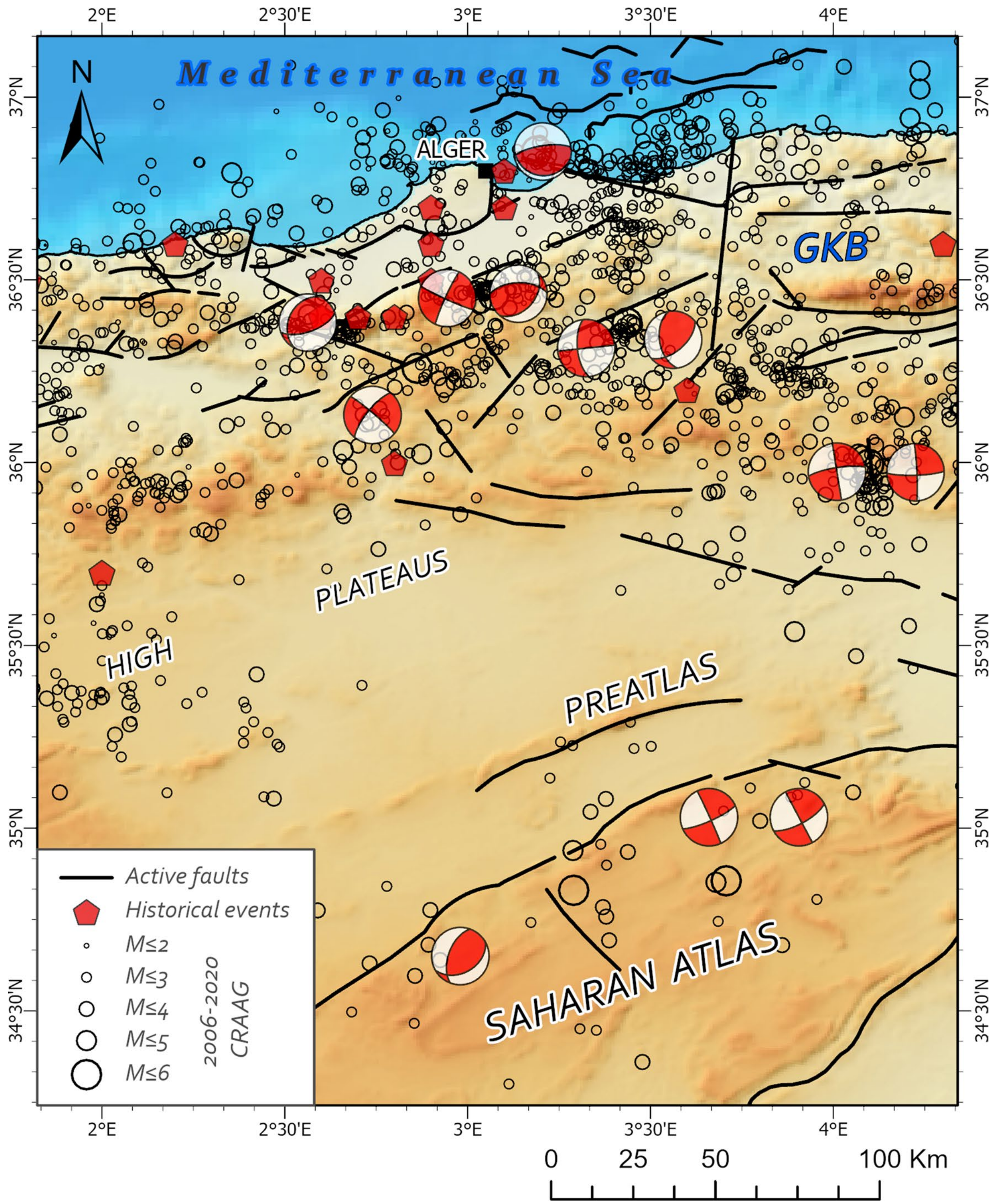


Fig. 11 The Central region's seismotectonic map. Seismic events are represented by black circles, active faults are represented by black lines, and historical events are represented by red circles. Beachballs are focal mechanisms

transfer between the different active faults of the Algiers margin (Yelles-Chaouche et al. 2009b; Beldjoudi 2020).

Further south, the Hammam Melouane 2013–2016 (FM10, FM12, Fig. 4) and Oued Djer 2018 (FM15, Fig. 4) sequences continue to be important manifestations of the southern Mitidja Basin borders reactivation (Yelles-Chaouche et al. 2017b; Mohammedi et al. 2020). These events occurred in an area with a history of intense seismicity, albeit without a clear characterisation of fault sources (Harbi et al. 2017a, b; Maouche and Harbi 2018). The analysis of current seismicity reveals the complex nature of this edge, which is cut by numerous transverse strike-slip faults.

Other sequences in this region can be found further south in the Tellian nappe belt and the surrounding Neogene basins. The occurrence of the Medea sequence in 2007 (Mw 5) (Dabouz et al. 2021) is one example, affecting the southern boundary of the Blida Atlas mountain in the Medea basin. Further east in the Tablat Range, a seismic sequence occurred near the village of Mihoub in 2014 (FM 13, Fig. 4) and again in 2016 (Semmane et al. 2017; Khelif et al. 2018).

According to the 2006–2020 catalogue, there is also moderate activity in the Saharan Atlas Mountains between Bousaada and Djelfa, with the strongest events in the Djelfa area (April 2, 2006, Mw 5.1, FM 2, Fig. 4). The North Atlas Fault highlights the boundary between the Atlas and pre-Atlasic domains.

7.3 The western Algerian region

Seismicity in the western part of the country has remained slightly weak and sparse compared to other regions of northern Algeria over the last 15 years (Fig. 12). Seismic events in the Middle Chelif basin did not exceed magnitude 4.0. In the last 15 years, there has been no evidence of the El Asnam Fault reactivating. Near Ain Defla, around the Doui Mountains, and along the northern boundary of the Oursenis belt, the most active seismicity was recorded. Figure 12 depicts an N–S-oriented cloud between Ain Defla and Chelif, containing microtremors ($M < 4$) as well as moderate events such as the Beni Haoua earthquake on April 25, 2012 (Mw 4.8).

Another activity area is around the Dahra massif, where many events occurred both at sea and on land, particularly near the Abou El Hassen and Tadjena faults on the Dahra's southern edge. Two seismic events with Mws of 5.2 (FM 3, Fig. 4) and 4.7 (Beldjoudi 2011) were recorded in 2006 and 2008, which could be related to activity along the Boukadir Fault. The seismicity occurred on the Mostaganem Plateau, located on the western edge of the Dahra. The 2014 Mw 4.9 earthquake (Semmane and Khelif 2018; Abbouda et al. 2018) was the most significant event, demonstrating a fault-fold reactivation in this area, particularly the Bouguirat Fault (Abbouda et al. 2018).

The southern edge of the Lower Chelif Basin shows activity near Relizane and Oued Rhiou, which could be explained by the Relizane Fault System.

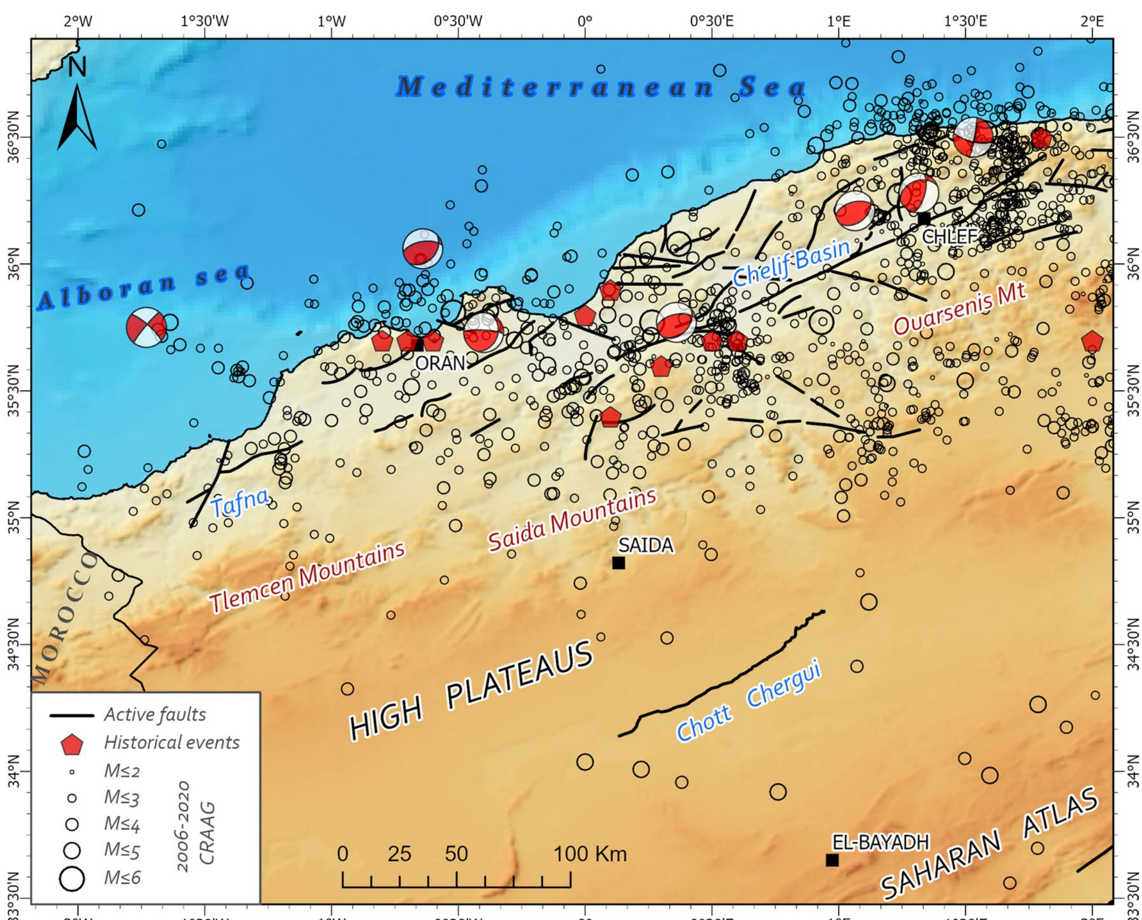


Fig. 12 The western region's seismotectonic map. Seismic events are represented by black circles, active faults are represented by black lines, and historical events are represented by red circles. Beachballs are focal mechanisms

To the west, the two Oran events of 2006 and 2008 remain the most significant (Benfedda et al. 2020). The first Mw 4.7 event occurred on the mainland near the village of Boufatis, 30 km southeast of the city of Oran, and was most likely caused by an active structure in the Habra basin. The second Mw 5.5 earthquake occurred offshore (FM4, Fig. 4) 30 km NE of Oran and was felt strongly by the population, but no human or material losses were reported. The offshore extension of the Murdjadjo anticline corresponds to the reverse focal mechanism. This occurrence could be related to the one in 1790.

We can see a lack of seismicity in the Mesetian domain, represented by the High Plateaus, further south of the Neogene basins. There are, however, some of low to moderate magnitude (Md 4.8) in the vicinity of Chott El Gherbbi. Finally, activity can be seen in the western branch of the Saharan Atlas, where a diffuse cloud can be seen as well as two notable earthquakes: The first one in 14th December 2009 near El Abiod Sidi Chikh (Md: 5.0), and the second one near Aflou in 2012 (Md 4.9). These occurrences demonstrate that the Atlas domain can reactivate in the current stress environment.

8 Discussion

Over the last two decades, significant efforts have been made to improve the Algerian seismic catalogue. Part of these efforts has been devoted to historical seismicity, with the analysis of archives from the French occupation periods significantly enriching Algerian catalogues (Harbi's catalogues). In the central and eastern regions, a large number of new historical events have been discovered. However, with the exception of a few significant events that occurred in Algiers, the medieval and Turkish periods are little known. The Turkish archives are an important piece of the puzzle in completing the Algerian catalogue from 1516 to 1832. Historical events are frequently unconstrained in terms of location and intensity estimates. As a result, it is necessary to reevaluate these events whenever possible in order to refine their parameters. For example, the Oran earthquake of 1790, with an intensity of X, has always been considered a major event in Algeria. However, a recent review of this event indicates a new magnitude estimate of Mw 5.5. (Chimouni et al. 2018).

The current catalogue addresses a major challenge: extending previous catalogues to the most recent period. It has the distinction of being the most accurate ever compiled for the Algerian territory because it is based on the country's most efficient network. The catalogue aims to inform interested parties about the large number of small events that occurred during the time period covered by this study, as well as to update the various seismic maps. This catalogue will aid in estimating seismic risk by predicting long-term seismicity and realising more reliable studies in various fields of seismology.

However, if we suppose this catalogue reflects a more realistic picture of the seismicity in northern Algeria, we need to solve several constraints before it is considered complete. One of the main issues is that network station coverage needs to be improved because several regions, such as the High Plateaus, border areas with Tunisia and Morocco, and the southern regions (the Hoggar's), need to be more instrumented. The installation of several OBS (Ocean Bottom Seismometers) stations in the offshore region are required to understand better the low-level seismic activity that has yet to be recorded. The network's northern coverage will impose additional constraints on locating margin seismicity, as today, the Spanish network's Balearic stations help us to constrain our coastal events.

Installation of more seismic stations in the Algerian territory will also help to reduce uncertainties of the various seismic parameters. For instance, for focal mechanisms, it will avoid referring to foreign agencies. Furthermore, because multiple stations are still single-component, installing three-component broadband stations will improve source parameter determination, such as depth determination. Another way to enhance parameter determination is to improve the current velocity model. We must capitalise on a number of key projects, such as Spiral, which provided new data to improve velocity models.

The macroseismic data required to release the isoseismal maps necessitate the use of new modern techniques for data collection. In contrast to the previous method of sending individual EMS 98 bulletins to different authorities, we are now collecting data through a web-based platform. Once the strong motion network expands, we will also incorporate shake maps.

Based on information from the 2006–2020 catalogue, it is now planned to revisit historical events in the Blida, Algiers, and Biskra regions, as was recently done for the Oran event of 1790, taking into account the significant results obtained recently in these areas. This type of research should be expanded to include various critical events. While the historical and recent catalogues are complementary, the location of the sources or seismogenic regions must be delineated based on the installed digital network.

Finally, the recent identification of several seismogenic zones, such as the area of the bay of Bejaia, the area of the north Constantine fault, and the bay of Algiers, is a significant step forward in improving seismic risk assessment. A major future challenge will be to model the deformation pattern of seismic sources and slip distribution on faults using GPS and Seismological Networks data.

9 Conclusions

The 2006–2020 catalogue summarises Algeria's recent seismicity over the last 15 years. It corresponds to the period when Algeria's first digital seismic network was installed. Thousands of events have been recorded for the first time, with an average of 600 events per year. This is a significant difference from previous seismic catalogues, reflecting the recent increase in the number of scientific papers published.

Each event in the 2006–2020 catalogue is represented by its seismic parameters. The focal mechanisms are computed for moderate to strong events.

For the first time, the catalogue provides a more realistic picture of seismic activity in Algeria. It emphasises the significant seismic activity in the country's east compared to the west. The ADSN network recorded a moderate event in the Hoggar region. Another event associated with induced seismicity was also discovered, highlighting the activity of a stable platform and introducing new driving forces.

The 2006–2020 catalogue enhances previous historical catalogues by identifying the most likely seismogenic sources responsible for historical events. Current seismotectonic studies in the field have increased the catalogue's precision.

The 2006–2020 catalogue is an essential tool for delineating new areal zoning and reassessing Algeria's seismic hazard.

Finally, the publication of the 2006–2020 catalogue as a supplement to previous historical catalogues is a tribute to Harbi Assia's important work to improve historical seismicity investigation.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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