Available online at https://asric.africa/natural-sciences
ASRIC Journal on Natural Sciences Vol 3 (2) (2023) 1-7

African Catalogue of Earthquakes (ACE)

Djillali Benouar[1*]

[1]Algerian Academy of Sciences and Technologies (AAST)

*Corresponding author: dbenouar@gmail.com

Abstract
The African Catalogue of Earthquakes (ACE) Project aims to establish a comprehensive earthquake catalog for the African continent to understand earthquake distribution and assess seismic hazards. Earthquakes pose a constant threat to several African countries, whether in North Africa, South Africa, East Africa, or West-Central Africa, causing loss of life and significant economic damage. Factors such as urbanization, development of critical infrastructure, and population concentration in hazardous areas have increased the need for accurate seismic hazard assessments. The project methodology involves retrieving and revising both macroseismic and instrumental data, standardizing seismicity assessment, completing available data, and creating a comprehensive earthquake catalog. The catalog includes information such as date, time, location, focal depth, magnitudes, epicentral intensity, and references for each earthquake. The seismicity of Africa is analyzed in different seismotectonic regions based on plate boundaries and geological features. The project involves relocating hypocenters, determining magnitudes, and developing intensity-attenuation relationships specific to each seismotectonic region. Plate-kinematic modeling using focal mechanisms and GPS data helps understand tectonic plate motions in the region. Documentary sources, seismological bulletins, and seismograms are used to gather information on past earthquakes. Intensity assessment is performed using established intensity scales as Medvedev-Sponheuer-Karnik (MSK) or European macroseismic (EMS98), and isoseismal maps are constructed to visualize intensity distribution. Calibration of historical earthquakes involves establishing magnitude-intensity relationships. The final output is a comprehensive earthquake catalog for Africa, providing homogeneous, complete, and accurate data for seismic hazard and risk evaluations. The project enhances the understanding of current tectonic activity and enables long-term seismic hazard assessments. It also emphasizes the importance of modern space-geodetic methods for seismic research. The methodology and data processing ensure a high degree of homogeneity for the continent, resulting in a valuable resource for seismic hazard assessment.
Keywords: Historical seismicity, Macroseismic data, Instrumental seismicity, Magnitude determination, intensity estimation, Africa, Catalogue of Earthquakes. Seismic hazard assessments.

General Methodology
This section presents the general methodology used to re-evaluate the seismicity of the African continent, based on procedure developed during a re-evaluation of the seismIcity of the Maghreb region (Benouar et al., 1996; Benouar, 2005). The general procedure (Figure 1) requires (1) the retrieval and revision of both macroseismic and instrumental information, (2) the development of a standardised methodology for the assessment of seismicity, (3) the application of techniques of completing the homogenised available data, (4) the establishment, for the whole continent, of as homogeneous and complete an earthquake catalogue as the available data allow today, (5) the geographic distribution of the earthquakes in order to define the seismic source zones in the region, (6) the calibration of regional earthquakes according to specificities of each defined seismotectonic region and (7) the derivation of intensity-attenuation relationships in the seismotectonic regions of Africa. This work completed will allow the future (re)assessment of seismic hazard in the African continent with a uniform degree of reliability. It considers two distinct periods. The first period involves extending the analysis back before 1900, as far as the available data allows. However, there are challenges in determining the precise timing during this period due to historical records expressing time using various calendars or time systems. The use of different calendars that are not directly convertible into modern standards poses a constant challenge in Africa. The

second period spans from 1900 to the present and focuses on the last two centuries. This period is characterized by significant advancements in instrumental seismology and the presence of adequate seismological services operating in and around many African countries. Homogeneous earthquake data for events above a certain magnitude could be obtained for the entire continent during this period. However, there were instances of reduced overall detection capability, specifically during the unstable years between 1914 and 1922 and again between 1940 and 1947, when certain stations and services were permanently or temporarily suspended. Additionally, the development of national seismographic stations in several countries marked this period.

In the methodological flowchart (Figure 1), the aspects most pertinent to the ACE Project are highlighted in pink tone. For historical earthquakes (pre-instrumental events) and even for twentieth century earthquakes for which there are no instrumental data, but for which intensities and radii are available, their magnitudes will be calculated from macroseismic data (using calibration relationships).

2.1 Instrumental information

Earthquake instrumental recordings in and around the African continent started late in the last century and were by today's standards very limited. The first instrument in North Africa was installed by 1900 in Egypt and in 1917 in Algeria. It is important to know about the historical development of seismographic station network in and around the African continent.

2.1.1 Seismological bulletins

Monthly bulletins of various seismological stations and international organisations should be used along this study for checking the event itself, completing and/or determining missing characteristics of the event. The main seismological bulletins to be consulted in this study are those of the International Seismological Summary (ISS, 1913-1963), the International Seismological Centre (ISC, 1964-1982) and the National Earthquake Information System (NEIS, 1983-present).

2.1.2 Seismograms

Seismograms are the fundamental observational records to study the various parameters of earthquakes and earth's interior. They are recorded at seismographic stations all over the world and are usually stored locally. The relocation of hypocentral location will be mostly accomplished using original seismograms, as well as bulletin phase data if waveforms are missing.

2.2 Relocation of Hypocentres

The relocation of hypocentres is a fundamental problem in seismological observations and research. In regions well covered with seismographic stations, it is believed that instrumental locations are more precise than macroseismic epicentres. However, this is not the case of most of African countries where neither the quality of the data nor the azimuthal distribution and number of stations is suitable for an accurate epicentral location, particularly before 1960. Whenever the instrumental data permits, it is imperative that earthquakes before 1960 be relocated, using the present-day ISC procedure and/or the Engdahl-van der Hilst-Buland (EHB) method used for the "Centennial Catalogue" (1900-1999) of global seismicity (Engdahl and Villasenor, 2002), in order to obtain a reliable geographical distribution of epicentres, which may lead to a better seismotectonic interpretation so that hidden features are revealed.

2.3 Determination of Magnitudes

The magnitude scale allows an objective classification of earthquakes with regard to size, independently of local ground conditions and environment. The aim in this study is to determine anew or to revise and to unify existing magnitudes; it is to produce a file of reliable data that could reflect, as homogeneously and completely as possible, the seismicity of the African continent.

Body-wave magnitude m_b will be calculated using Gutenberg and Richter formula:

$$m_b = \log(A/T)_{max} + Q(D,h) + S \qquad (1)$$

where $(A/T)_{max}$ is the maximum amplitude-period ratio in the wave classes (PV, PH, PPH and SH) and Q(D,h) is a calibrating function which depends on epicentral distance D, focal depth h and wave type.

Surface-wave magnitude M_S will be calculated using the Prague formula given by:

$$M_S = \log(A/T)_{max} + 1.66\log(D) + 3.3 \quad (2)$$

where $(A/T)_{max}$ is the maximum value of the ration of the ground displacement amplitude in microns, T is the corresponding period in seconds and D is the focal distance in degrees.

For the early years of the last century, when Milne seismographs were operating, M_S is calculated using the Ambraseys-Melville calibration formula given by:

$$M_S = \log(2A_t) + 1.25\log(D) + 4.06 \quad (3)$$

Where $(2A_t)$ is the double trace ground displacement amplitude (peak-to-peak) in millimetres and D is the focal distance in degrees.

For a variety of reasons, many earthquakes in the African continent will remain without surface-wave magnitudes or simply without any type of magnitude. To solve this problem, M_S will be estimated, when possible, from semi-empirical relationships, derived in this work, between M_S and m_b or M_S and M_L or by using the number of stations that reported the event to the ISS or ISC. M_S for historical earthquakes may also be estimated from the radius of perceptibility (r_3) which is defined as the mean epicentral distance of an area within which the shaking was felt with intensity equal to or greater than III (MSK) by using a relationship between M_S and r_3, or by using the relationship between M_S and I_o. Naturally, these semi-empirical relations will be developed for specific regions in Africa.

2.4 Seismotectonic Analysis

The African continent straddles the boundary between the Nubia (NU) and Somalia (SO) plates. The main areas of seismic hazard on the continent can be related to the slow (order of millimetres per year) relative movement between NU, SO and the surrounding plates.

2.4.1 Seismotectonic region definition

In ***Northern Africa***, the NU-Eurasia (EU) plate boundary in the Maghreb region has produced major earthquake disasters such as affected Lisbon and the Morocco coast in November 1755 and the Algiers region in May 2003. In the Eastern Mediterranean, the NU-Aegean Sea (AS) and NU-Anatolia (AT) plate boundaries constitute a localised system in which relative motions are an order of magnitude faster (~30 mm/yr). This seismotectonic region poses the main threat of tsunami destruction along the North African coast, such as the great event in the year AD 365 that destroyed the ancient city of Alexandria. Along the NU-Arabia (AR) plate boundary in the Dead Sea rift zone and Red Sea, relative motions range between 4 mm/yr in the north and ~15 mm/yr in the south, near the Gulf of Aden.

In ***Eastern Africa***, the northern NU-SO rift zone between Eritrea, Djibouti, Somalia and Ethiopia presents both earthquake and volcanic geohazards to this region. Farther south, in southern Sudan, Kenya, and northern Tanzania, the NU-SO rift is split between a western NU-Victoria (VI) branch and an eastern VI-SO branch. In southern Tanzania, Malawi and northern Mozambique, these western and eastern rift branches pass southwards into the boundaries of a separate Rovuma (RV) plate, namely, the NU-RV and RV-SO boundaries, respectively. In southern Tanzania and the Mozambique Channel, the RV-SO boundary crosses the African continental margin in the Western Indian Ocean (WIO).

In ***Southern Africa and the adjacent (WIO) region***, the RV-SO boundary recrosses the continental margin in the southern Mozambique-Swaziland-South Africa area, and continues southward to the Southwest Indian Ridge (SWIR). East of longitude ~28°E, the SWIR forms the slow-spreading (~14 mm/yr) NU-Antarctica (AN) plate boundary until it joins at a triple junction with the SO-Capricorn (CC) along the Centrial Indian Ridge and the AN-CC boundary along the SE Indian Ridge. Because the national territories and Exclusive Economic Zones (EEZs) of certain African Union states such as South Africa (Marion and Prince Edward islands), Mauritius and Seychelles lie close to these eastern boundaries of the SO plate, a complete ACE Project should also cover these WIO regions, including the north-eastern SO plate boundaries with the Indian (IN) plate in the Carlsberg Ridge and the AR plate in the Gulf of Aden. Within Southern Africa, in Zambia, Zimbabwe, Botswana, Namibia and South Africa, there are developing "proto-rifts" along a possible NU-Transgariep (TG) plate boundary (Hartnady, 2002).

In ***Central and Western Africa,*** the seismic hazard is mostly of an "intraplate" nature, sometimes associated with hotspot-volcanic lineaments, such as the Cameroon Volcanic Line or the Cape Verde Islands-and-seamount chain, or with neotectonic reactivation of continental margin fracture zones, such as the Ghana margin with the oceanic Romanche Fracture Zone. In this region, the western limits of the NU plate, along the NU-North America (NA) and NU-South America (SA) plate boundaries should be included within the ACE Project study area.

2.4.2 Plate-Kinematic Modelling

For an objective seismotectonic analysis along the different plate boundary segments in the wider ACE Project area, the most important data sets are the classic "first-motion" focal-mechanism determinations for earlier events, and the Centroid Moment Tensor (CMT) catalogue that has accumulated since the start of the era of the Global Digitial Seismographic Network (GDSN), i.e., from ~1977 to the present-day. For those parts of the ACE region that lie beyond the continental margins of Africa, e.g., along the peripheral NU-EU, NU-NA, NU-SA, NU-AN, SO-AN, SO-CC, SO-IN, SO-AR, NU-AR, NU-AT and NU-AS plate boundaries, the post-1977 CMT data will form an important ancillary ACE element.

When combined with directional information from onland or submarine fault mapping, the CMT data yields unambiguous earthquake slip vector (ESV) information. In further combination with "absolute-motion" data for the NU and SO plates, derived from GPS and other space-geodetic methods (e.g., Hartnady et al., 2004; Calais et al., 2006) within the International Terrestrial Reference Frame (ITRF), the ESV data provides a powerful additional constraint for the determination of directions and rates of relative motion along all of the various ACE plate-boundary segments. A precise knowledge of tectonic rates and directions is crucial to the reliable and timely assessment of seismic hazard in Africa, because – at typical millimetre-per-year rates - the recurrence interval of the largest (major to great) events is so long (on the order of thousands of years) that earthquake catalogues alone are unrepresentative of the true hazard. Such knowledge is also central to the objective definition of seismic source zones for improved probabilistic and deterministic seismic hazard assessment.

2.5 Macroseismic information (literary sources)

Documentary source materials are essential for a retrospective reconstruction of the macroseismic field data of past earthquakes. However, it is clear that the results of any study based mainly on an inventory of data available from various sources, is subject to the quality and completeness of the information. Thus, the earthquake data available today will determine the accuracy of this work and the significance of the conclusions drawn. Sources of information will be found in local and European documentary materials, newspapers, administrative records, special studies, scientific reports, private diaries and various books. Such materials are found to be available in libraries and archive centres across African countries.

2.5.1 Existing catalogues

Although catalogues or listings of earthquakes in Africa are available, they cover different regions or countries, time periods, incomplete at a given region, and are grossly deficient in several respects, particularly in magnitude, depth and location. Some of these catalogues are new, some incomplete for any given region or time period, some out-of-date or at best second hand, some others are oversimplified and misleading.

The first task is to make an inventory of all existing catalogues, covering the whole continent or particular parts of it and also different periods under investigation, and to compare and combine their entries. These existing catalogues, despite their incompleteness and inhomogeneity, constitute important references, in terms of both felt and recorded seismic activity, and should be considered as the starting point for the revision of the seismicity of the region under consideration. Additional macroseismic information, collected during this project, will be used to answer ambiguities among previous catalogues.

The recent Centennial catalogue (Engdahl and Villasenor, 2002) provides a convenient starting basis of the ACE Project. In order to ensure a common global standard of completeness and uniformity of comparison across all continents, this catalogue adopted a lower "cutoff magnitude" of 6.5 (M_S as preferred reference scale) for the "historical period" (1900-1963) and a magnitude of 5.5 as lower cutoff for the "modern period" (1964-1999). In Africa, however, there are relatively few earthquakes with M>6.5 in the historical period, and cutoff magnitudes of 6.0 (historical) and 5.0 (modern) might be more appriopriate here for the delineation of its major seismotectonic features.

In principle, the ACE Project should aim to include all recorded earthquakes, irrespective of size, and over a much longer period than that covered by the global Centennial catalogue. In some parts of Northern Africa, e.g., the Nubia-Arabia boundary along the Dead Sea Rift Zone, the documentary record of historical events can be traced back over millennia, rather than centuries. Arabic documents dealing with north-eastern and north-western (Maghreb) Africa provide important inputs to some existing earthquake catalogues (Ambraseys et al., 1994; Benouar, 1994).

2.5.2. Contemporary Accounts

These documentary sources could be classified under two general headings, which are: (1) official reports and (2) general public information (local and foreign newspapers). The first type includes published and unpublished scientific works, official reports, administrative correspondence, private letters and military records. The second type of document, although written for public consumption, generally presents the effects of the event according to the geographical and political circumstances. Some of these reports contain detailed information, mentioning names of damaged cities, villages, tribes and even buildings, houses and streets, behaviour of the population and animals, effects on nature, relief operations, photographs and interviews with people. This type of archival data will play a major role in the revision of the knowledge of the seismicity of the African continent. From these accounts, generally, one is able to retrieve the historical context during which the earthquake occurred.

2.5.3. Other Documentary Sources

Another new source of information appearing during the twentieth century is unpublished technical reports related to the construction of large engineering structures. Most of these reports contain invaluable information accumulated in situ by engineers or geologists after an earthquake or in specific studies made to evaluate local seismic hazard.

2.6. Intensity Assessment

Intensity assignment presents also one of the main reasons for inhomogeneity. Intensity value is usually attributed in terms of different scales, sometimes even unspecified. Newly retrieved data should be re-assessed according to one suitable scale and correlate the old data with it. Intensities in this study will be re-assessed with reference to the Medvedev-Sponheuer-Karnik -MSK- (1981) or the European macroseismic (EMS98) intensity scales, using standard criteria and macroseismic information retrieved from various sources mentioned earlier.

For a wise analytical study of past earthquakes, and better understanding of the information contained in the contemporary sources, one should take into account the political, socio-economic and demographic conditions, times of peace or war, cultural and religious backgrounds as well as the building stock characteristics of the period concerned. From these factors that may influence the macroseismic information, the buildings play a major role in the frame of intensity estimations. Because the building stock in the African countries have numerous variable characteristics such age, building materials and structural systems, an extensive investigation was carried out in order to reveal whatype of constructions were exposed and what state they were in during the period of the concerned earthquake.

In this research work, Intensities IX and higher will be assigned to the sites where destruction was complete (intensity depending on the nature of buildings) and there was great loss of life. Broadly, this means that within the area containing the fault-breaks associated with the earthquake, masonry and adobe structures were totally destroyed, many of which collapsed completely, causing casualties. Intensities VI to VIII are consistent with a rigid interpretation of the MSK or EMS 98 intensity scales. Lower intensities IV to V will be attributed solely on felt effects and on evidence of lack of damage to low-quality types of constructions. For the very low intensities II to III, negative reports were also considered; generally, in the absence of very low intensity observations, intensity III^{+} is assumed to be the boundary of the felt area.

2.7. Isoseismal maps

An intensity map, that is the distribution of observed intensity data points of an earthquake, is the best compromise between the qualitative nature of historical records and the quantitative needs of the users. An intensity map illustrates at a glance how good is the knowledge of the earthquake itself; the total number of intensity data points, their density and azimuthal coverage can be used for assessing quality factors.

From intensity data when enough, an isoseismal map is constructed and a macroseismic epicentre located for each studied earthquake. Radii (R_i) and intensity (I_i) are reported in the catalogue. The location of macroseismic epicentres is of great value, in terms of tectonic feature determinations, particularly during the first half of this century when instrumental data were still unreliable. As an output of the processing of isoseismal maps, attenuation relationships are derived.

2.8. Calibration of Historical Earthquakes

The calibration of historical earthquakes represents the magnitude-intensity relationship model for the region under survey. One of the results of the revision of the data set is the derivation of a relationship from which the surface-wave magnitude Ms can be estimated from macroseismic information for specific regions in Africa. This can be achieved by fitting the pairs Ii and Ri with their corresponding surface-wave magnitude Ms.

The derived relationship, which represents the equivalent surface-wave magnitude, M_{sc}, in terms of felt effects, could be used to assign magnitudes to historical and even to 20th century earthquakes which have no instrumental data but for which isoseismal radii and intensities are available.

2.9. New Catalogue

All the previous section of this paragraph contributes to a homogeneous, complete and as accurate as possible catalogue. For most of the seismic hazard assessment methods, the earthquake catalogues represent the main, if not the only, seismological data sample and it is considered as the « maximum possible today » earthquake information in the region.

The structure of this catalogue should include: Serial number, Date: Year, Month and Day, Time of origin of the event: Hours, Minutes and Seconds in Universal Coordinated Time (UTC), Instrumental epicentre: latitude and longitude, Macroseismic epicentre: latitude and longitude, Focal depth, Magnitudes: M_S, mb, M_L and M (unspecified), Epicentral intensity, Number of reporting stations: NS, Site of maximum felt intensity, References, Remarks.

The catalogue should go back in time as far as possible to extend the seismic history of the continent.

3. Conclusion

This methodology and the consistent processing of the available data, particularly magnitude determinations and intensity estimations, will ensure a high degree of homogeneity for the African continent. It will produce an earthquake catalogue for the whole continent, as homogeneous and as complete as possible as the available data allow today, which can be used in new seismic hazard and risk evaluations. The catalogue compiled in this work will be stored as a computer file for ease of use, and the widest possible public dissemination. The last years have seen an important development of methods and computer routines for the assessment of seismic hazard. For most of these methods the catalogue presents the main, if not the only, seismological data set, and it is assumed as the "maximum possible" information, upon which the evaluation of seismic hazard and risk relies to a large extent.

Nevertheless, to examine the current tectonic activity pattern or assess long-term seismic hazards in a specific region, it is crucial to extend the seismic information as far back in time as possible. If such historical data is not available, the innovative utilization of modern space-geodetic methods becomes essential. These advanced techniques can compensate for the lack of extensive historical records and provide valuable insights into the seismic behavior of the region.

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