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AN EARTHQUAKE CATALOG OF MID-ATLANTIC RIDGE

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Abstract

The Mid-Atlantic Ridge (M-AR), which runs along the centre of the Atlantic Ocean, is one of the best known divergent boundaries. Seismic studies have been a crucial factor in deciphering the structure of the oceanic crust. For their performance a necessary prerequisite is the compilation of a reliable earthquake catalog of the broader area. In this study, an attempt was made to create an earthquake catalog of M-AR that could become a useful "tool" for large-scale seismological studies of this region. For this reason a very large sample of data from several seismological centers, as well as from already published catalogs of strong earthquakes, was collected and examined. ISC was considered as the main reference agency, while as reference magnitude scale the moment magnitude scale, M_W was adopted. The main goal was to identify and organize the best and most recent information available for earthquakes falling within the time window 1900-2014 and the space window bounded by the extended coordinates ~ 81° (N) to -51° (S) and 10° (E) to ~ -50° (W). After magnitude homogenization, check of focal depths and definition of completeness magnitude, a reliable and homogeneous earthquake catalog of M-AR consisting of 14,211 events was created, available for any seismological use and further study.
Keywords: *Complete homogeneous earthquake catalog, Moment magnitude, Magnitude completeness.*

Περίληψη

Η μεσο-Ατλαντική ράχη (M-AR), η οποία διατρέχει το μέσο του Ατλαντικού Ωκεανού, αποτελεί ένα από τα πιο γνωστά συστήματα αποκλινόντων λιθοσφαιρικών ορίων. Οι σεισμικές έρευνες συνετέλεσαν σημαντικά στην αποκρυπτογράφηση της δομής του ωκεάνιου φλοιού. Για την πραγματοποίησή τους απαραίτητη προϋπόθεση είναι η ύπαρξη ενός αξιόπιστου καταλόγου σεισμών την ευρύτερης περιοχής. Στην παρούσα εργασία έγινε μια προσπάθεια για την δημιουργία ενός καταλόγου σεισμών της M-AR που θα μπορούσε να χρησιμοποιηθεί ως «εργαλείο» για ευρείας κλίμακας σεισμολογικές μελέτες της περιοχής. Αυτό επιτεύχθηκε μέσω της συλλογής και επεξεργασίας ενός μεγάλου όγκου δεδομένων από διεθνή σεισμολογικά κέντρα και δημοσιευμένους καταλόγους ισχυρών σεισμών του παρελθόντος. Ως κύρια πηγή αναφοράς χρησιμοποιήθηκε το ISC, ενώ η κλίμακα μεγέθους που υιοθετήθηκε είναι αυτή του μεγέθους σεισμικής ροπής (M_W). Κύριος στόχος ήταν ο εντοπισμός και η οργάνωση, βάσει κριτηρίων, των καλύτερων και πιο πρόσφατων διαθέσιμων πληροφοριών για τους σεισμούς που εντάσσονται μέσα στα όρια συντεταγμένων των ~81° (Β) έως -51° (Ν) και 10° (Α) έως ~ -50° (Δ) και έγιναν κατά το χρονικό διάστημα 1900-2014. Μετά από την ομογενοποίηση των μεγεθών, τον έλεγχο αξιοπιστίας εστιακών βαθών και του καθορισμού μεγέθους πληρότητας, δημιουργήθηκε ένας

ομοιογενής κατάλογος σεισμών της M-AR που αποτελείται από 14.211 σεισμούς που έγιναν κατά το χρονικό διάστημα 1900-2014.
Λέξεις κλειδιά: *Πλήρης ομοιογενής κατάλογος σεισμών, Μέγεθος ροπής, Μέγεθος πληρότητας.*

1. Introduction

Mid-ocean ridges are the largest mountain chains of great geological importance and the most active volcanic systems. Mid-ocean ridges are essentially spreading centres where two oceanic lithospheric plates move apart. As plates move away from each other molten rock emerges from great depths. Some molten rocks rise up to the seafloor, producing volcanic eruptions and long volcanic chains. The magma that reaches the ocean seabed freezes and solidifies onto the divergent plate boundaries creating new oceanic crust (MacDonald, 1990). During this process the older crust is pushed away from the ridge in a transporter belt fashion. This process is known since the early 1960's as sea-floor spreading and this is why the mid-ocean ridge is also known as a "spreading centre" or a "divergent plate boundary" (Hess, 1962).

Mid-ocean ridges are ruptured by offsets perpendicular to the ridge (MacDonald, 2001), known as transform faults. Transform faults are structured by the pressure of the up welling new basaltic magma. At mid-ocean ridges earthquakes can be detected along ridge, as well as on related transform faults. They often occur in swarms (Sykes, 1970) and are mostly of low magnitude with shallow epicentres (Heezen, 1960) due to the small thickness of the solid crust. In most cases, fault-plane solutions imply both normal (due to the extensional system of the ridge) and strike-slip faulting (along transform faults) (Frisch *et al.*, 2011).

Maybe one of the best known divergent boundaries, which is just one section of the global mid-ocean ridge system, is the Mid-Atlantic Ridge (M-AR) which runs along the centre of the Atlantic Ocean (Fig. 1). This mountain range expands apart at rates of 1 to 2 cm per year (Hekinian, 1982), extending from the Arctic Ocean up to the southern tip of Africa. Despite its relatively slow spreading rates, the ridge has a deep rift valley along its crest, imprinting the location at which the two plates move apart. This rift includes the area of seafloor spreading in which the molten magma continuously rises, cools, solidifies and is gradually pushed away from the plate boundaries. This process is demonstrated by the fact that older sea floor slides away from mid-oceanic ridges toward continents as it is replaced by the new pulled out sea floor. Evidence for this process comes also from paleomagnetic striping on the sea floor (Mason and Raff, 1961; Vine and Matthews, 1963). Apart from a spreading centre, M-AR is also characterized by volcanic activity and earthquakes. Despite the fact that the overall description of the procedures that take place beneath mid-ocean ridges (and therefore the creation of new seafloor) is well known, there are still many questions which remain to be answered by further study.

One of the most important "key-tools" for a detailed seismicity study and earthquake research is the creation of a homogeneous earthquake catalog of the region of interest. Historical data from descriptions of earthquake events are usually incorporated with more accurate instrumental data. Earthquake catalogs are fundamental components for seismicity studies such as seismic zonation and seismic hazard assessment. In this study, an attempt was made to create a homogeneous, in respect to magnitude, reliable earthquake catalog of the M-AR (Fig. 1) with a multidisciplinary use.

2. The data

The main data sources were the bulletins of several globally operating agencies, such as the International Seismological Center, ISC, the U.S Geological Survey, USGS, the National Earthquake Information Center, NEIC, the Global Centroid Moment Tensor group, GCMT, as well as several published earthquake catalogs (Pacheco and Sykes, 1992; Engdahl and Villaseñor, 2002). The overall goal of this compilation was to identify and critically organize the best and most recent information available for earthquakes falling within the time window 1900-2014 and space window bounded by the extended coordinates almost 81^0N to -51^0S and 10^0E to -50^0W (which encompass the broader region of interest). This procedure was accomplished through a merging process of all the earthquake catalogs provided by the respective seismological centers (where magnitudes were available). As the main reference agency we used the ISC, while the adopted magnitude scale was the moment magnitude scale.

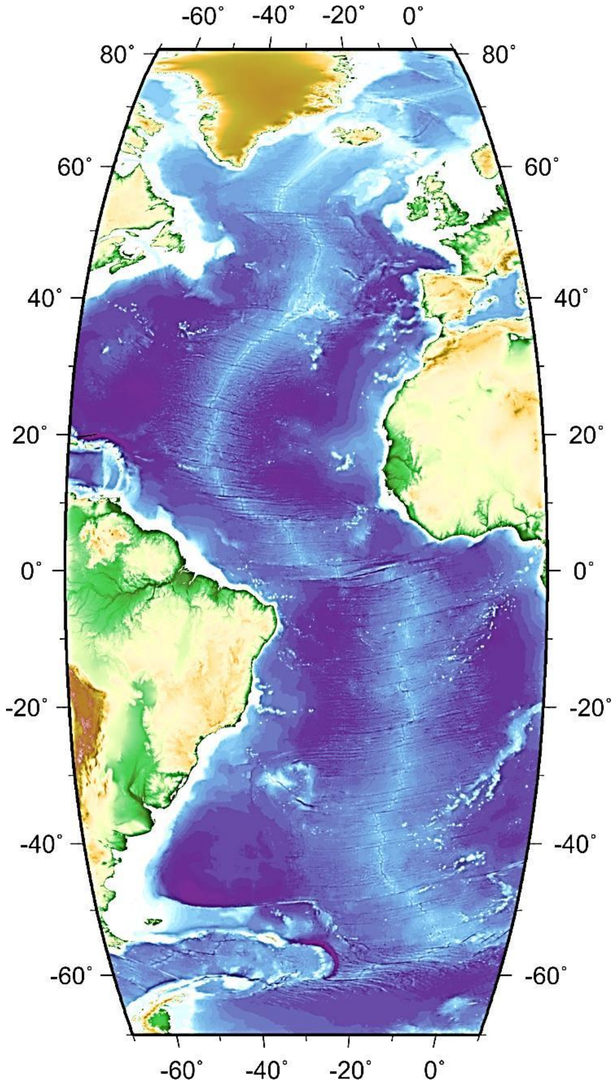

Figure 1 - Map of the Mid-Atlantic Ridge (M-AR).

3. Homogenization of magnitudes

As mentioned earlier the employed initial catalog provides magnitude values estimated in various scales, such as surface wave magnitude (Gutenberg and Richter, 1936; Gutenberg, 1945a), M_S, the body wave magnitude (Gutenberg, 1945b, 1945c), m_b, and the local magnitude (Richter, 1935), M_L. All these magnitude scales do not scale linearly with the seismic energy for all magnitude ranges. Moreover M_L, M_S and m_b scales suffer from saturation at different magnitude levels. Both these restrictions constitute a major problem for earthquake research and may lead to overestimation or underestimation of earthquake magnitudes.

Due to these limitations, Kanamori (1977) and Hanks and Kanamori (1979) proposed a new magnitude scale, namely the moment magnitude, M_W. Moment magnitude, which is controlled by fault size and dislocation, does not saturate. This is due to the direct proportion of moment magnitude with the logarithm of seismic moment, leading to a uniform behavior for all magnitude ranges. Therefore, M_W can be considered as the most reliable and accurate magnitude scale for earthquake size description (Heaton *et al.*, 1986; Johnston, 1996; Shedlock, 1999; Papazachos *et al.*, 2002; Utsu, 2002; Scordilis, 2006; among many others). Hence, for the creation of combined M-AR earthquake catalog we adopted as reference scale the moment magnitude. In cases with lack of estimated moment magnitudes, a magnitude conversion procedure was applied. More specifically, all magnitudes expressed in other magnitude scales were converted to moment magnitudes through existing converting relations. The relations applied for m_b and M_s conversions are the ones proposed by Scordilis (2006) and are based on data of globally occurred shallow earthquakes:

Equation 1

$$M_W = 0.67(\pm 0.005)M_S + 2.07(\pm 0.03),$$
$$3.0 \leq M_S \leq 6.1,$$
$$R^2 = 0.77, \quad \sigma = 0.17, \quad n = 23{,}921$$

Equation 2

$$M_W = 0.99(\pm 0.02)M_S + 0.08(\pm 0.13),$$
$$6.2 \leq M_S \leq 8.2,$$
$$R^2 = 0.81, \quad \sigma = 0.20, \quad n = 2{,}382$$

Equation 3

$$M_W = 0.85(\pm 0.04)m_b + 1.03(\pm 0.23),$$
$$3.5 \leq m_b \leq 6.2,$$
$$R^2 = 0.53, \quad \sigma = 0.29, \quad n = 39{,}784$$

As the moment magnitude of each earthquake we finally considered either the original moment magnitude, if such information was available, or the mean value of the converted magnitudes by weighting each participating value with the invert of the standard deviation of the respective converting relation. After the completion of this procedure, a homogeneous (in respect to magnitude) catalog with the focal parameters (location, depth and magnitude) of the earthquakes of M-AR was derived. The catalog contains 14,211 earthquakes, which occurred along the trace of the Mid-Atlantic Ridge (M-AR) or within its vicinity during the period 1900-2014, with moment magnitudes (original or converted) M_w=4.0-7.4.

4. Hypocentral depth control

It is well known that earthquakes in oceanic basins mainly focus along the spreading axis. These earthquakes exhibit mostly shallow depths (Heezen, 1960), while focal mechanisms display normal faulting on moderate submerged structures parallel to the ridge. Earthquakes with shallow depths also cluster along the transform faults which accommodate the differential motion between offset ridge sections (Bohnenstiehl and Dziak, 2008). As a result, we do not expect to detect intermediate-depth or deep focus earthquakes along M-AR. Nonetheless, preparing the M-AR catalog we found earthquakes with focal depths greater than 60 km.

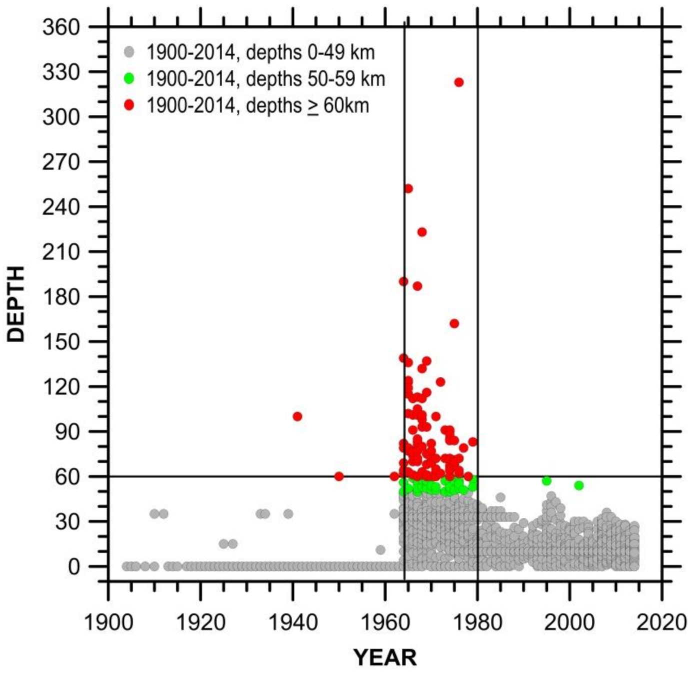

Figure 2 - Time distribution of the focal depths of M-AR earthquakes for the period 1900-2014.

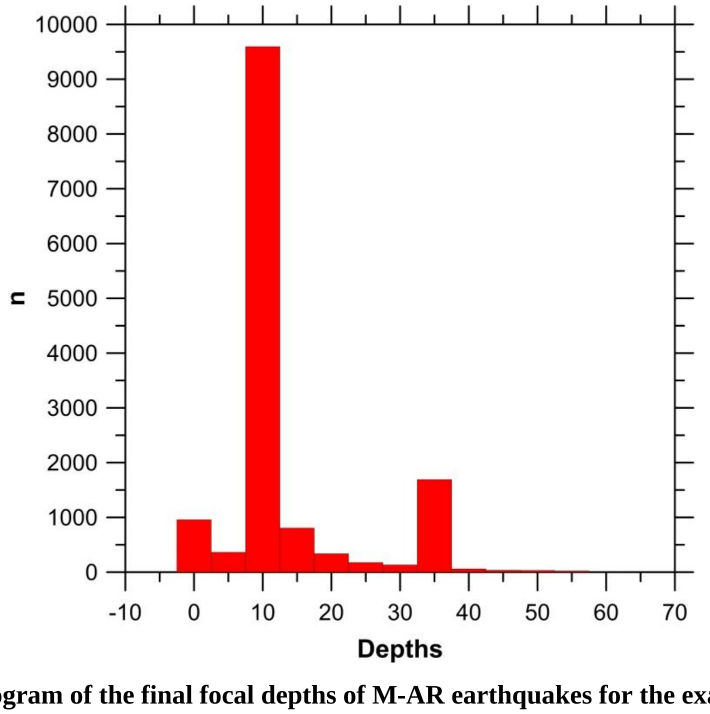

Figure 3 - Histogram of the final focal depths of M-AR earthquakes for the examined period (1900-2014).

More precisely, 96 out of 14,211 events had focal depths between 60 and 323 km. Based on this rather unexpected observation we studied the depth time distribution of these events in order to identify the time- period of their occurrence. The time distribution of the depths revealed a major cluster of earthquakes with intermediate focal depths within the period 1964-1980 (Fig. 2). According to ISC this discrepancy could be due to improved new practices adopted after 1980. Therefore the observed spread of focal depths estimated along M-AR is attributed to the absence of stations at close epicentral distances. In order to fix these depth issues we replaced the reported focal depths of those earthquakes (false deep events falling within the time window 1964-1980) with a nominal but credible standard depth of 33km.

Considering this adaption only three earthquakes display intermediate depths and they all fall within the time period before 1964. Following a re-assessment by ISC for events up to 1962, the updated data were all included to our data set. Following this catalog update, the depths' histogram (Fig. 3) and the time distribution of depths (Fig. 4) were created to check how the depth values of the revised catalog were distributed. It is obvious that the whole region is dominated by shallow earthquakes, the majority of which have occurred at focal depths 0-30km. Figure (5) shows the spatial distribution of the earthquakes of the final catalog using four magnitude scales ($M_w \leq 4.0$, $4.0 < M_w \leq 5.0$, $5.0 < M_w \leq 6.0$ and $M_w > 6.0$).

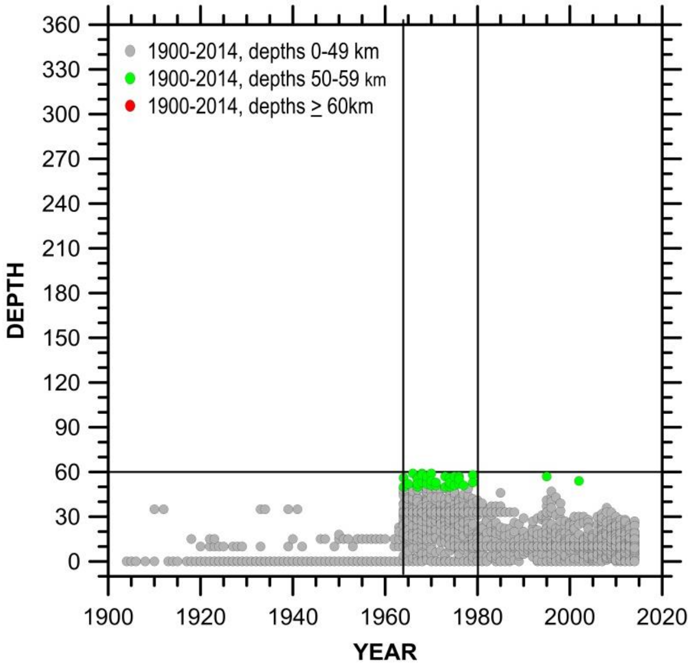

Figure 4 - Time distribution of the final focal depths of M-AR earthquakes for the period 1900-2014.

5. Seismicity rates

The time distribution of regional earthquakes can be defined by the frequency of their occurrence, which actually presents the number of earthquakes occurred in this region per unit time. As seismicity rates are considered the number of earthquakes within specific space, time and magnitude intervals, normalized by the length of the corresponding time interval. Understanding the time evolution of seismic activity is of great importance for seismicity studies. Short period changes in seismicity rates can be attributed to the occurrence of large events while long period changes usually correspond to changes of the completeness magnitude. Moreover, valuable information on the mechanical state of likely dangerous seismic asperities can be drawn by seismicity rates and consequently, such quantitative measures of seismicity changes may be employed for prediction purposes (Marsan and Wyss, 2011).

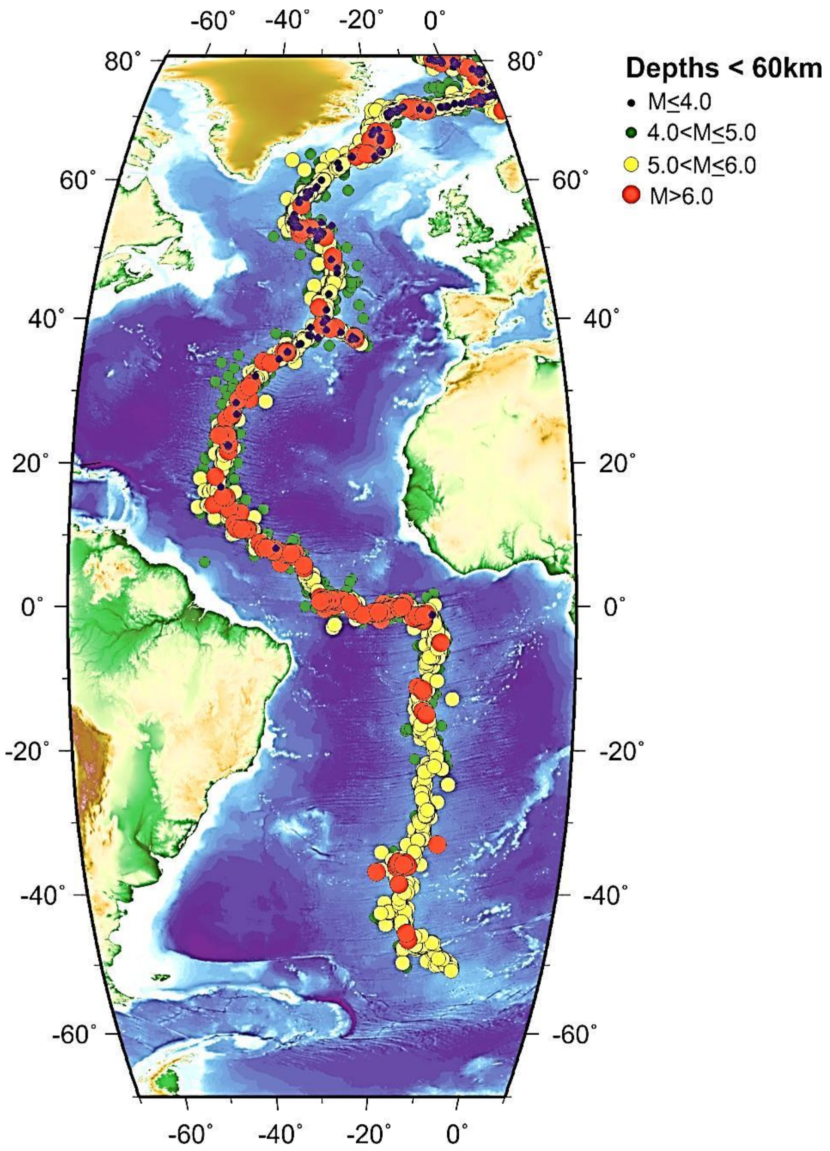

Figure 5 - Epicentral map of M-AR earthquakes of the period 1900-2014, based on the final earthquake catalog presented here.

We have studied the rates of the seismic activity of the M-AR using rates calculated for the entire catalog of the M-AR starting at 1964 for magnitudes ranging from 3.8 to 5.0. The results were illustrated by line scatter plots of the cumulative number of earthquakes with respect to time (years). The corresponding plot for earthquakes of magnitude ≥4.0 and for the time period 1964-2014 is presented as an example in Figure (6).

Observing this seismicity rate plot (Fig. 6) we can identify an intense and abrupt change of the earthquake cumulative number around 1995. This pattern was also observed for regional rate estimations along the whole M-AR. Such a change would occur if only at the specific time an abrupt increase of seismic activity (e.g. a strong earthquake) or a significant densification of the regional seismic networks had occurred, assumptions that are clearly not valid. Following communication with ISC, it is suggested that this change in seismicity rate is an artifact attributed to the opening of the Experimental/Provisional IDC (GSETT-3: a test of an experimental international seismic monitoring system). Specifically, the UN Conference on Disarmament's Group of Scientific Experts (GSE), in order to test new and revised concepts for an International Seismic Monitoring System (ISMS), through its third global technical test (GSETT-3), made an effort to conduct an operationally realistic test of rapid collection, distribution and processing of seismic data using a global network of seismographs of modern technology (Ringdal, 1994). In addition, seismicity rates of M-AR were also calculated for time period 1900-2014 for several magnitude classes. Those rates will contribute to the estimation of magnitude of completeness, for several successive time-periods, as thoroughly analyzed below.

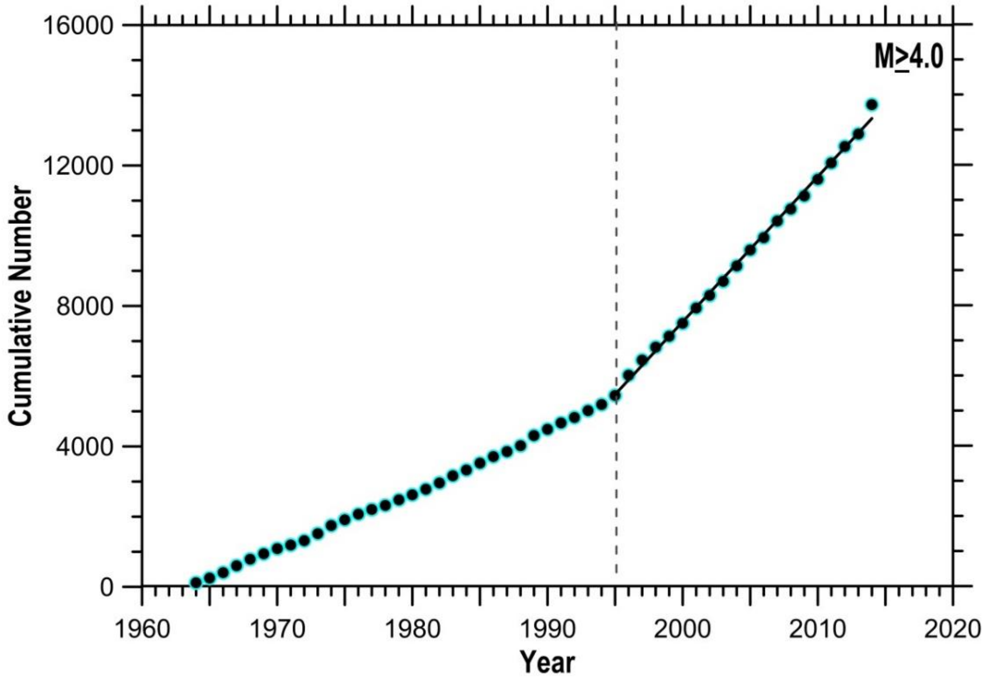

Figure 6 - Seismicity rate of M-AR earthquakes with M≥4.0 for the period 1964-2014.

6. Gutenberg-Richter distribution

Several scientists have proposed over the years functions between the number of earthquakes and their magnitudes (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944). The relationship with the most extensive use nowadays in seismology is the Gutenberg-Richter (1944) power law which is expressed with the following equation:

Equation 4

$$\log N_t = a_t - bM$$

This equation shows the relationship between the magnitude, M, and the total number, N_t, of earthquakes of magnitude $\geq M$, which occurred within a specific region during a certain time-period. Parameter a_t depends on the time and space covered by the data, as well as seismicity level. Parameter b is one of the most important parameters in seismology; this importance stems from the fact that it describes the material homogeneity (level of fracturing) and the stress-status of the examined area.

The magnitude of completeness (M_c) of an earthquake catalog represents the minimum magnitude above which all earthquakes within a space-time window are included. The accurate knowledge of M_c and its variation in space and time is essential for estimating seismicity parameters representative of the region and the time interval of the data.

Considering the whole catalog of the M-AR, as it was prepared in this study, we attempted to define its M_c and its variation with time. Since our data before 1920 were sparse, we decided to check the completeness variation within the time interval 1920-2014. Three distinct time intervals are revealed (Fig. 7): 1920-1963 with M_c~5.8; 1964-1995 with M_c~5.0; 1996-2014 with M_c~4.7. As the M_c values for the two last periods are relatively similar we decided to merge them confining the completeness periods in two: 1920-1963 with M_c~5.8 and 1964-2014 with M_c~4.9.

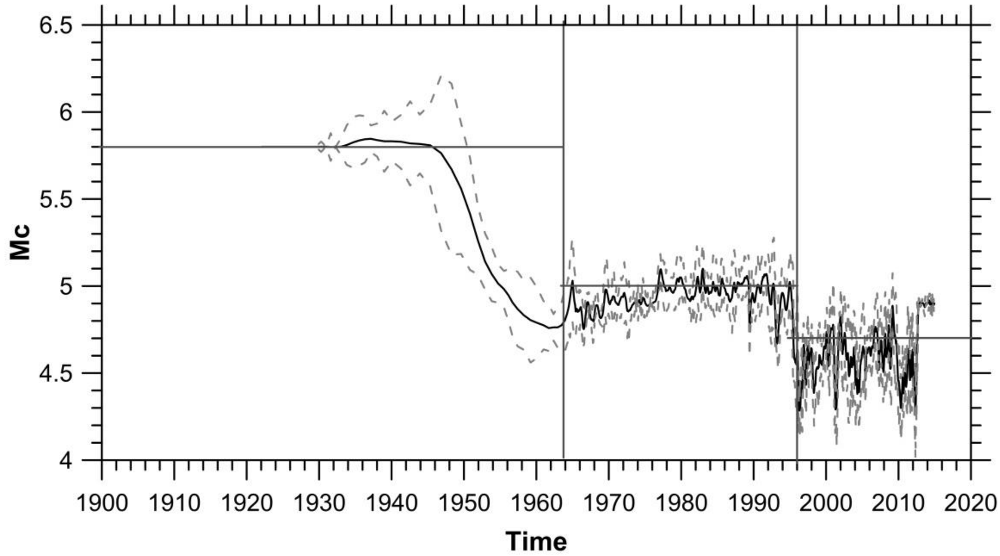

Figure 7 - Time distribution of completeness magnitudes of M-AR earthquakes for the period 1900-2014. The dashed lines represent the confidence intervals after bootstrapping the data.

To check and improve the above results, the magnitude completeness was also checked by the Gutenberg-Richter (G-R) distribution for the above two time-windows (see Fig. 8a, b) and by the seismicity rates for considering several possible M_c values (see Fig. 9a, b, c). Figures (8a), (9a) and (9b) confirm the selection of M_c=5.8 for the period 1920-1963, however, the seismicity rates rather favor the adoption of the more conservative value of M_c=6.0. The diagrams that were obtained from the G-R distribution (see Fig. 8b) and rates (see Fig. 9c) for the second time interval (1964-2014) the adoption of M_c=4.9 is confirmed.

7. Discussion

A homogeneous, with respect to magnitude, and reliable earthquake catalog of the Mid-Atlantic Ridge was generated based on a very large sample of data from several international seismological sources. The catalog provides information on the focal parameters of the earthquakes which occurred in this region during the period 1900-2014. For the catalog's homogeneity, the moment magnitude scale was adopted. All magnitudes that were measured in other magnitude scales were converted into this scale by using known and globally valid empirical relations (Scordilis, 2006). The reported hypocentral depths of the earthquakes of the catalog were carefully examined revealing a number of intermediate-depth events before 1980. Those cases were an outcome of the unfinished procedure of the Bulletin Rebuild of ISC.

The focal depths of the events prior to 1964 were also adopted after bulletin recheck performed by the ISC. Beyond the quantitative control, a quality control of the edited catalog was performed as well. The study of the catalog's completeness, with respect to magnitude, revealed two complete periods: the first extending from 1920 up to 1963 with cut-off magnitude M_c=6.0 and the second from 1964-2014 with M_c=4.9. The final catalog contains 14,211 earthquakes, which occurred along the trace or the Mid-Atlantic Ridge and close to it during the period 1900-2014, with moment magnitudes (original or converted) M_w=4.0-7.4. This catalog may be used for large scale seismicity studies of the covered region.

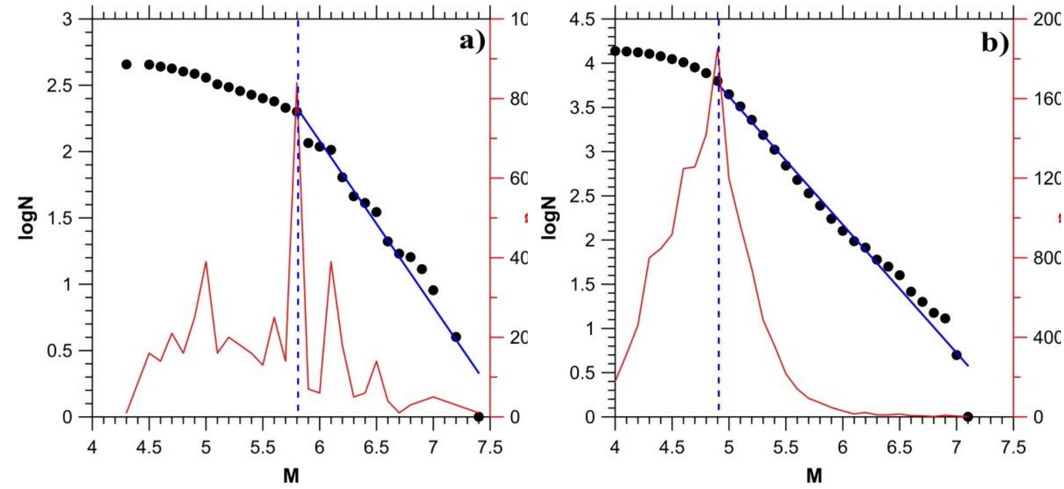

Figure 8 - Gutenberg-Richter distribution of M-AR earthquakes for two time intervals: a) 1920-1963 and b) 1964-2014.

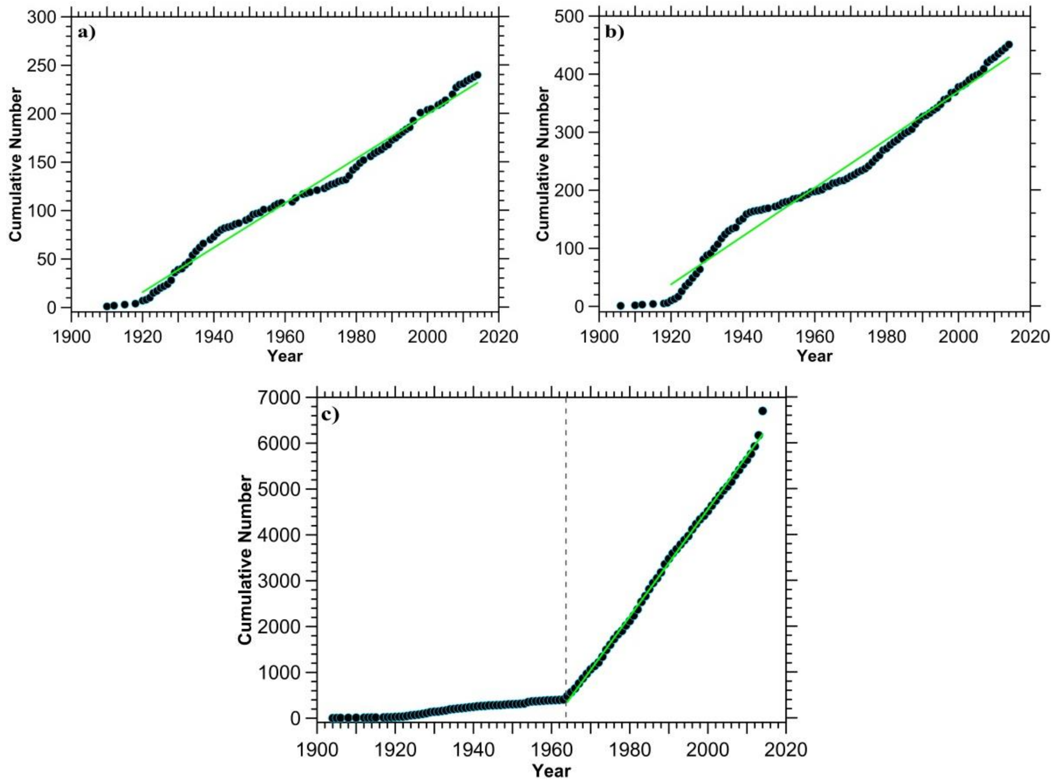

Figure 9 - Seismicity rates of M-AR earthquakes for three magnitude ranges: a) M≥6.0, b) M≥5.8 and c) M≥4.9.

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