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Research Article

Mining Activities and the Spatial-Temporal Variations of Earthquakes in Southern Africa

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Abstract
Spatial-temporal variations in earthquake occurrence have been studied in many regions of the world but little can be said about the Southern Africa Region in this regard. Using earthquakes of magnitudes greater than or equal to one together with the FORTRAN language and Generic Mapping Tools (GMT), spatial variations of earthquakes spanning the period 1966 to 2014 were examined for the region. Similarly, the temporal variations with earthquakes of magnitudes greater than or equal to four were studied. The spatial analysis showed that the highest number of events (1438) in the period occurred at an average depth of around 7.5 km representing approximately 79.9 % of the total earthquakes considered. The temporal distribution of events on the other hand showed that the highest number of events (590) were recorded in the year 1993. Three main issues were identified as potential factors responsible for the observed variations. Activities such as mining and failures in weak zones of the rock mass as well as increase in the number of stations were identified as the key factors responsible for the observed distributions. The third factor could not be independently verified. However, earlier studies suggest that this factor indeed have caused major earthquakes in the region.

Keywords
Seismicity—spatial and temporal variations—spatiotemporal—subduction rate

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1. Introduction

Natural as well as human activities occurring over a period of time and space have long been identified as factors contributing to the variations in the incidence of earthquakes reported in the past. For instance, human activities such as vehicular traffic and machinery operations resulting in ambient noise have been identified as some of the major factors contributing to temporal variation in apparent seismicity rate of earthquakes with magnitudes greater or equal to one by Atef et al [1]. The frequency of earthquake in a region is also said to be influenced by changes in atmospheric conditions such as pressure and temperature. Under special circumstances, the frequency of earthquake has been found to have a corresponding relationship with yearly changes in atmospheric pressure [2]. Thingbaijam et al [3] in a study, described the seismicity of a region as consisting of the ongoing earthquake processes and long-term historical seismic activities as well as expectations for the occurrence of future large earthquakes. By employing the spatial distribution of b-values the study successfully quantified the seismicity patterns and also delineated broad seismic source zones and the potential maximum earthquakes in each zone for the study region.

The Southern African region is not traversed by any of the major tectonic plate's boundary but rather located in the interior of the large African plate. The borders of this plate to the south are located in the mid-Atlantic and mid-Indian ocean ridges (Fig. 1).

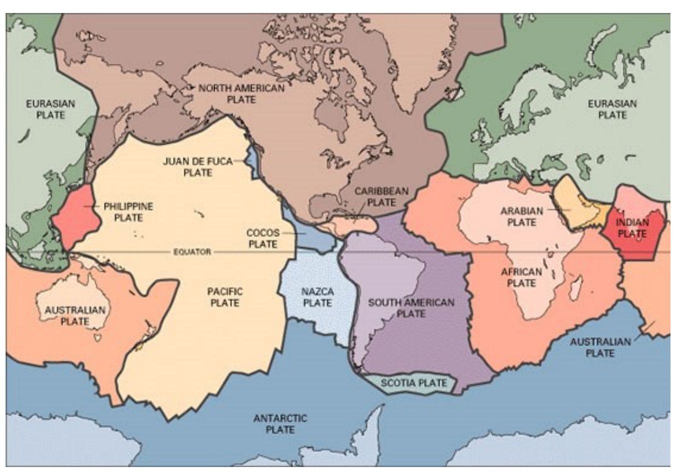

Figure 1. Plate Tectonics Map by USGS [4]

The continent does not appear to be affected by the distant tremors of this belt. The East African rift system is a clear line of intra-plate seismicity, which has been shown to extend to Southern Africa. Large magnitude earthquakes are found to be of tectonic origin. Over 90% of the epicenter of global natural earthquakes occur at the boundary of major plates. Seismic activities in this region are categorized to be of the type that result from intra-plate activities which may occasionally reach critical values. They are found to be sporadic, scattered and shallow. A typical example is the events of December 8^{th}, 1976 in Welkom, Orange Free State scale that reached the magnitude of 5.5 [5, 6].

Gane et al [7] indicated that the incidence of earthquakes in the Johannesburg area has been a feature since the 1908. The observation according to the authors were made after mining for over twenty years. It was noted that these tremors were regularly felt in Johannesburg and its surrounding areas but with different shaking strengths. In fact, the activities of mining have been reported as a major contributor to the generation of seismic events. Uzoegbo and Warnitchai [5] in a study of seismicity in the Southern African region concluded that most of the seismic events of magnitudes below 5M originated in the mining areas. However, it was noted that the epicenters of mine tremors are usually lower than 2 km and are hazardous only in the immediate vicinity of the mines. The natural earthquakes on the other hand have a much lower frequency of occurrence but are much more hazardous to the region. Also, Durrheim et al [8] on assessing the risks posed by large seismic events in the gold mining districts of South Africa noted that a seismic event of magnitude 5.3 (local Richter magnitude scale) which occurred on 9 March 2005 was attributable to past mining operations. Additionally, the authors noted that seismic events will continue to occur in the gold mining districts as long as deep-level mining takes place and are likely to persist for some time even after mine closure.

Though mining continue to be a major contributor to the activities of earthquake in the region, other factors have also been reported. Linzer et al [9] reported of a massive earthquake of magnitude 7.3 (local Richter magnitude scale) recorded on 23 February 2006, in the vicinity of a village called Massangena in the southwestern part of Mozambique. The authors noted that the earthquake occurred at the southernmost extension of the East African Rift System. Though seismic activities in the East African Rift is common, the magnitude was unexpectedly large. This the authors concluded was because of the faulting mechanism associated with diverging plate boundaries which generally produces smaller seismic events. Pule and Saunders [10] also noted that seismicity in Mozambique is associated with tectonic activities along the East African Rift which forms the boundary between the African plate in the west and the Somalian plate in the east.

Cases of contaminated seismic catalogs by activities of mines have also been reported elsewhere. Mackey et al [11] investigated the temporal variation of over eighty-seven thousand events in North-Eastern Russia and concluded that activities of coal and gold mining, quarry and construction indeed had a great influence on recorded seismic activities in the region than was previously thought. Fritschen [12] studied mining induced seismicity in the Saarland mine of Germany and stated that there was a direct relation between the mining activities and seismicity in the area. The study also indicted that strong seismic events were as a result of shear failure and occurred at different depths indicating mining was influenced by tectonic stresses.

Spatial and temporal variations in earthquake occurrence have indeed been studied in many regions of the world but little can be said about the Southern African Region in this regard. Available literature has shown reports of various aspects of earthquake studies focusing on individual countries constituting the Southern African Region especially South Africa. However, many of these studies either concentrated on studies dealing with source mechanisms of mine related seismicity, the upper mantle seismic structure beneath the region, the risk associated with these activities and the frequency-magnitude characteristics in seismic events [13, 14, 15, 16]. In a region dominated by mining operations, it is very important to monitor the spatial and temporal variations of seismic activities induced by these operations to provide valuable information for the purposes of planning. In spite of the many publications on earthquake studies in the region, the authors are yet to come across a study dealing comprehensively with the Southern African Region as a whole with respect to studies concentrating on the spatial and temporal variations of the occurrence of earthquakes. The absence of such a study was therefore the motivation for this current work. In this study, we have identified and suggested factors that are believed to be the major contributors to both spatial and temporal variations of earthquakes in the Southern African Region.

2. Materials and methods

In this study, earthquakes of magnitudes greater than or equal to one (1) were downloaded from the Advanced National Seismic System (ANSS) for the purposes of determining the occurrence of earthquake events in the Southern African Region. The total area considered was 30^o x 20^o. The area encompassed countries such as Namibia, Botswana, South Africa, Mozambique, Zimbabwe and part of the Indian Ocean (Fig. 2).

Data spanning the periods from 15^{th} March, 1966 to 25^{th} October, 2014 with a total of 1799 events were considered. The authors consider this range sufficient for a proper understanding of seismic activities in the region over the years. To ensure the data obtained were relevant to the study, lines which were considered irrelevant were removed. It is important to note that no declustering of the catalog from ANSS was done. The final data used consisted of six columns. The first column of the data contained information about the year, month and day of an earthquake event. The hour, minute and second at which an event occurred is found in column two. Columns three and four stored the information of the latitudes and longitudes of the event respectively. The depth at which an event occurred is found in column five and finally column six stored the magnitude of the event.

Southern Africa is well known for its rich mineral resources. For this reason the region has seen a lot of mining and related activities over the years. It is home to many of the mining companies operating in Africa. The study chose this region to examine if these activities have any influence on earthquake events recorded over the years. The raw data from ANSS was plotted on the region using a GMT program and the result is as shown in Fig. 2. To appreciate the distribution of events in the spatial context, a FORTRAN program was written that counted the number of earthquakes at different focal depths with intervals of 5 km apart. A GMT program that plotted the number of events in each interval against the midpoint of the interval was then created as shown in Fig. 3. Temporal variation of events was also determined by a similar FORTRAN and GMT programs. In this case, the program counted only earthquakes with magnitudes greater or equal to 4.0 for each year and then the total earthquakes were plotted against each year (Fig. 4).

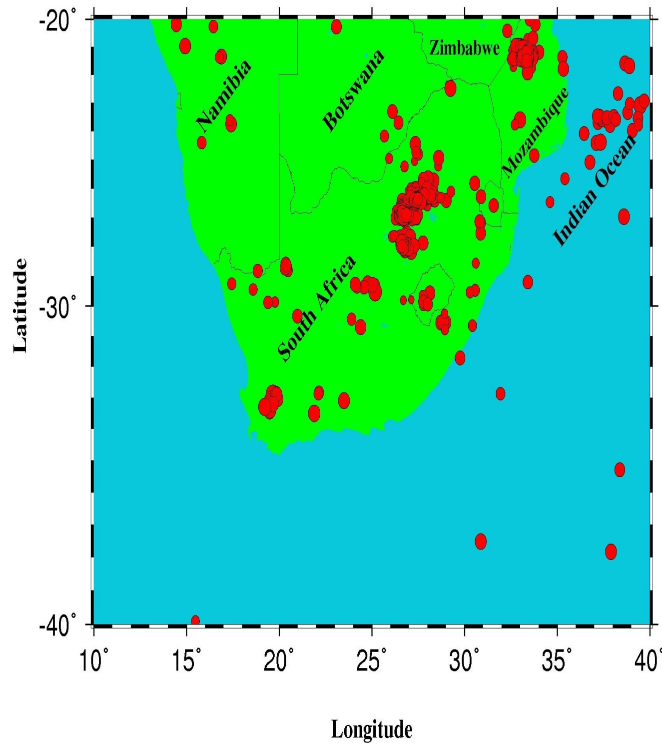

Figure 2. Earthquake distribution in the region of study

3. Results

Plotting of the earthquake data for the period under study on a map for the Southern African region showed a large concentration of events in two main countries namely South Africa and Mozambique (Fig. 2). South Africa however recorded more earthquakes in comparison to Mozambique. Most of the earthquakes in South Africa are observed to be concentrated within the regions bonded by longitudes 26^o to 34^o and latitude -28^o to -20^o. Also, isolated concentration of earthquakes is observed in the southwestern part. Earthquake events in Mozambique on the other hand are more concentrated in the regions between longitudes 33^o to 35^o and latitudes -22^o and -20^o. Namibia, Botswana and Zimbabwe showed fewer occurrences of earthquakes relative to that of South Africa and Mozambique. Quite a great amount of events were also recorded on the part of the Indian Ocean sharing borders with Mozambique. These events were mostly observed between longitudes 36^o to 40^o and latitudes -25^o to -23^o (See Fig. 2). The large amount of earthquake concentration in the three regions of South Africa, Mozambique and part of the Indian Ocean suggest that these regions have special characteristics or features that are associated with seismic activities.

Exploring further the behavior and distribution of earthquakes in the region, a spatial distribution of the data was constructed (Fig. 3). The total number of earthquakes at a uniform interval was determined and the result plotted against the midpoint of each interval.

A look at the result indicate that earthquakes recorded were generally between 0 and 33 km of focal depth. However, three intervals within this range showed the highest number of earthquake occurrences deserving further highlighting. The interval between 5 and 10 km recorded the highest number of earthquakes (1438) among all ranges. This figure represents approximately 79.9% of the total earthquakes counted for this scenario of the study. The second highest number of earthquakes (190) representing 10.6% of the total earthquake events occurred in the interval between 10 and 15 km while 6.7% of the total number earthquakes were observed in the interval 30-35 km. The remaining depths recorded a total of 51 earthquakes representing 2.8% of the total earthquakes. It is also worth mentioning that, the least number of earthquake recorded was one and was at a focal depth interval of 60-65 km. Some depths recorded no earthquakes and are therefore not highlighted here. The important observation in the distribution is that most of the earthquakes occurred in the depth range of 5-15 km, suggesting there might be a catalyst for seismic activities at these depths.

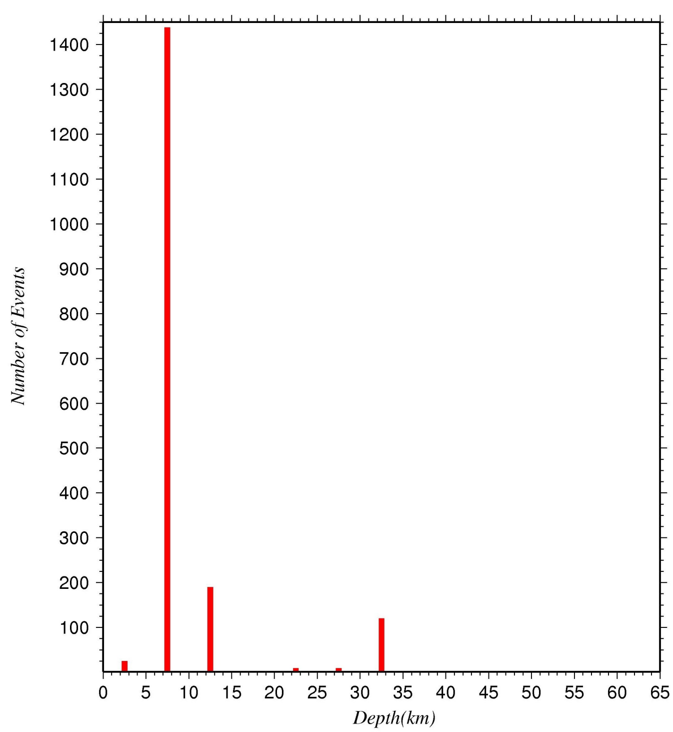

Figure 3. Distribution of earthquakes at different focal depths at intervals of 5 km

Fig. 4 shows the variation in the number of earthquakes recorded per time (years) with magnitudes greater or equal to 4.0. To appreciate the interesting trends shown, we looked at the result in three categories namely; years with earthquake numbers equal or greater than 100, those with numbers between 50 and 99 and finally those with numbers 49 and below.

For the period of forty eight (48) years considered, five different years (1990, 1993, 1994, 1996 and 2006) recorded earthquakes numbering one hundred and above. This represents about 10.4% of all the events recorded during the period. Also, 1995 is observed as the only year to have recorded earthquake numbers in the range between 50 and 99 with the actual number of earthquakes being 80. Two of the years (1967 and 1978) recorded no earthquakes while between 1 and 49 earthquakes were obtained for the rest of the forty years. The highest number of earthquakes for the entire duration however were observed in 1993 (590 earthquakes). Very close to this value were 338 earthquakes which were observed in 1994. 106 and 109 earthquakes were recorded for 1990 and 1996 respectively. The least number of earthquakes of 2 were observed in the years 1976 and 1977. The rest of the years showed number of earthquakes far less in comparison with that obtained in 1993. The apparent concentration of events in the nineties seems to once again suggest something unique might have happened in those periods.

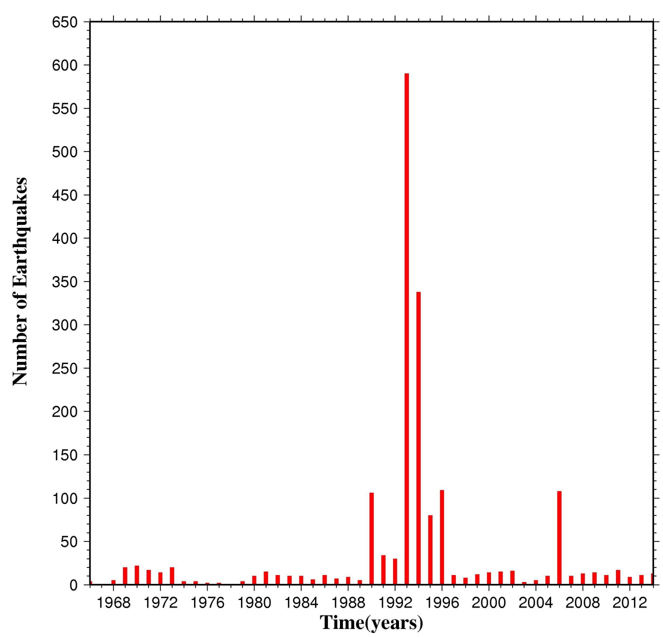

Figure 4. Distributions of earthquakes with magnitudes greater or equal to 4 over time

4. Discussions

Southern Africa is home to large deposits of minerals such as gold, diamond, aluminum and many others. The region has experienced over 1000 years of mining activities [17]. A human activity such as mining is considered a major inducer of seismicity and has been studied extensively

[18, 19, 14]. Indeed, the activities of mining often result in variations in stresses in the rock mass near and far from the area of excavation. These stress changes sometimes lead to violent failures. During such failures, waves similar to what is experienced when an earthquake occurs is emitted. These failure events are referred to as mining-induced seismicity. Gibowicz and Kijko [19] provided two broad classification of mine seismicity namely; mine operation related induced seismicity and seismicity due to movement on major geologic discontinuities. Also, factors such as station density and station operating characteristics have been identified among other factors as having a great influence on earthquake detection by networks and seismic b-values [1, 20, 21].

In the present study, some very interesting distribution of earthquake phenomena is observed in the region. The observed concentration of earthquakes in particular areas and the corresponding spatial and temporal variations of the earthquake activities in the study suggest that earthquake occurrence in the area is greatly affected by many unseen factors. A review of the main activities in these areas lead to the conclusion that the observed trends are due mainly to (1) mining activities and failures in weak zones of the rock mass; (2) the number of stations; and (3) a possible increase in the subduction rate at the boundary between the Indian ocean and Mozambique.

A quick google search on the number of surface and underground mines operating in the region suggest that there are over fifty mines operating in this region. For instance, most of the earthquakes in South Africa are found to be concentrated in the Far West Rand mining district of the Republic. The district is well noted for extensive underground mining activities and is reported to house some of the world's deep underground mines. Some of these mines are reported to be operating at depths from 2 km to 4 km. When a geologic environment has high concentration of brittle rocks, seismicity could easily become a common feature. The basic mining operations employed by almost all mines include drilling, blasting, loading and hauling. Though there might be some differences in the way each mine performs these operations; the general rule is that they all use explosives and heavy duty machinery resulting in the breaking and excavation of materials. All these activities have direct and indirect effect on rock mass and ground behavior which may lead to the triggering of an event. Again, rock fall, pillar failures, strata fracture, joints and faults and slip on bedding planes are all factors that produce seismic events and will be recorded by seismic stations installed in or around where they occur. These observations are largely supported by a recent study on induced seismic activities in deep mines and their effects for tectonic earthquakes. The study strongly suggested that the occurrence of seismic activities (with source-scaling properties consistent with tectonic earthquakes) in bedding planes, dikes and reactivated faults are great contributors to the phenomena [14]. Also, it been stated by Urbancic et al [22] that geological structures of varying size can be activated by the presence of mine workings in underground mines and their interaction with the local/regional stress fields. And that the location of these fractures is provided by the spatial distribution of seismic events. Based on several case studies in Canadian mines, the authors observed that mining induced microseismicity is associated with pre-existing fractures and contribute significantly to the seismic data.

Also, a 2012 report on mining in Mozambique by one of the largest professional services companies in the world, KPMG, listed 29 major local and foreign mining companies as having operations in the country [23]. This suggest that the high numbers of reported earthquakes could mainly be as a result of the different phases of mining activities going on in the country. Again, this conclusion is strongly supported by the work of [14] and the observation of [22].

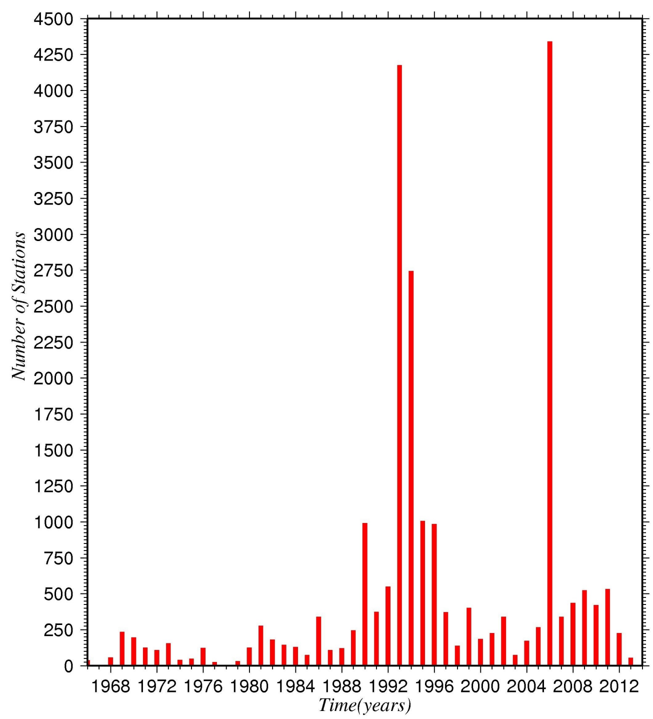

Figure 5. Number of stations used to locate earthquakes in each year

It is the author's believe that the observed temporal variations are mainly due to the improvement in the detection capacity over the years as the number of stations per year exhibit similar behaviors as the number of earthquakes per year (see Figs. 4 and 5). The high values of earthquakes per year observed for the years 1990, 1993, 1994, 1996 and 2006 in the author's opinion are as a result of the corresponding increases in the number of stations for those years. Just as shown in the temporal variation, the spatial distribution of number of earthquakes per focal depths and the number of stations per depth shows that higher earthquakes are recorded at depths with higher station density (Figs. 3 and 6). Though other factors may have contributed to these trends, the primary factor as observed in these cases is the increase in station density. This position is supported by the fact that areas with large station numbers do have the ability to capture earthquakes with magnitudes within the range considered for the present study [1].

The third factor attributed as one of the reasons for the variations observed in the study could not be verified independently in this study. The studies by Linzer et al [9], Pule and Saunders [10] nevertheless strongly supported this conclusion. Further investigations are however required to ascertain the extent to which this factor has influenced the events recorded.

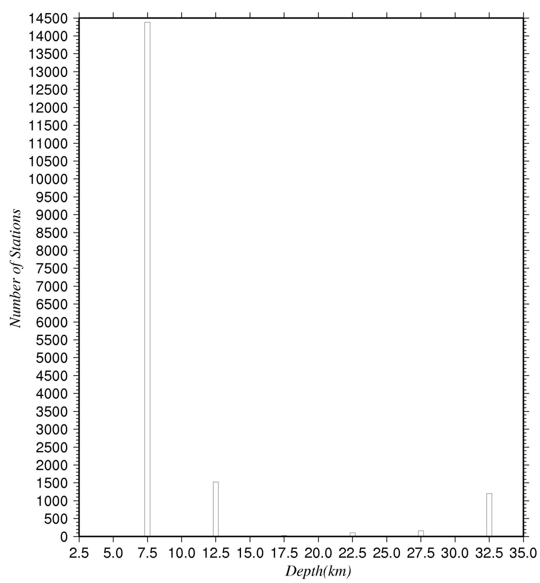

Figure 6. Number of stations used to locate earthquakes at different depths

5. Conclusion

Using seismic data spanning the period from 5^{th} March, 1966 to 25^{th} October, 2014, we studied the spatial and temporal variations in the occurrence of earthquake in the Southern African Region. The results of the study showed a large concentration of events in two main countries namely South Africa and Mozambique with South Africa recording the highest among the two countries. The temporal distribution of events showed that the highest number of events were observed in the year 1993. The spatial analysis on the other hand showed that the highest number of events in the period occurred at an average depth of around 7.5 km. The results from the spatial relation in particular are consistent considering that some of the deep mines in the area operate at depths of about 4 km. Our inability to establish the exact number of mines in the region remains one of the key limitations of this work. We are therefore working to establish this number so as to be able to pinpoint which mines contribute the most to recorded events and what triggers those events. In conclusion, the study identified mining activities and failures in weak zones of the rock mass as well as the increase in the number of stations as the key factors responsible for the spatial and temporal distribution observed. This study therefore provides the basis for further investigation into the spatiotemporal occurrence of earthquake in the region and a basis for forecasting.

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