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Full Length Research Paper

Time independent seismic hazard analysis of the afar depression

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A Bayesian approach is applied to conduct a seismic hazard analysis in Afar Triple junction, resulting in a spatial distribution of the probability of exceedance in 100 years for earthquakes of MSK intensities VI and VII. The highest values of the exceedance probability for intensity VII are relatively scattered, showing spatial distribution that conforms with the RRR (rift-rift-rift) relative translational and rotational motions of the three bounding (Main Ethiopian Rift-Southern Red Sea Rift-Gulf of Aden Rift). The spatial distribution of the probability of exceedance for intensity VI is similar, but in scope. Iso-curves of the probability of exceedance for intensity VI seem to strike in a NW and NE direction while the intensity VII distribution is characterized by NW, NE and E-W directions. The map of spatial distributions of the probability of exceedance indicates specific areas of high seismic hazard in the future in the study area.

Key words: Afar depression, Bayesian seismic hazard assessment, rift.

INTRODUCTION

The 300 km wide Afar depression is a diffuse extensional province marking a triple junction, where the plate boundaries represented by the Red Sea (Arabia-Nubia), the Gulf of Aden (Arabia-Somalia) and the Main Ethiopian rift (Nubia-Somalia) meet. The depression is divided into northern, central and southern sectors on the basis of its geology and geography. The northern portion of the depression is dominated by an axial volcanic range of shield volcanoes produced by basaltic fissure eruptions aligned in the NW-SW belt, parallel to the regional tectonic trend of the Red Sea. The central part is dominated by graben and horst structures that are occupied by Pliocene flood basalts and Quaternary sedimentary rocks and bounded to the east and west by axial volcanic centers. The Tendaho graben is one of the largest in the central sector. The southern sector of the depression is like-wise dominated by horst and graben. However, the graben structures are aligned in the NNE direction. The Tendaho Goba ad Discontinuity, a narrow NW to WNW trending fault zone separates the Central Afar from the Southern Afar and represents the northern extension of the Main Ethiopian Rift. The prominent NNE trending grabens occurring in the central parts of Southern Afar are the continuation of the Wonji Fault Belt, which is the axial rift zone of the Main Ethiopian Rift. The Gulf of Aden ridge has propagated into the African continent through the Gulf of Tadjura. The ridge continues in the WSW direction. The youngest volcanism currently erupts through the NW striking Asal-Ghoubat Rifts (Eagles et al., 2002).

Extensive and catastrophic destruction can occur during large earthquakes and vigorous investigations are required in seismic-prone areas to lessen loss of life and the economy. Of particular importance in risk mitigation for a given region is determining the likely size and impacts of future events, including, for example regional distribution of maximum probable earthquake and its associated effects is the scale or measurement of the earthquake effects in its regional distribution.

The seismic parameters of primary importance, in determining the scale of possible future impacts are those that can be measured instrumentally. In this region,

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however, seismic instrumentation has been spare and a descriptive quantity like intensity is utilized as a useful means of information in the quantification of earthquake effects. The historical seismic data, even in its shortcomings, is equally important in the investigation and study pertaining to the long-term pattern of seismic activity going on a particular region and related to earthquake hazards. The usefulness of intensity as another seismic parameter is the role taken in the empirical determination of its dependence to distance, focal depth and local conditions. The functional dependence provides estimates of earthquake effects within the epicentral region during the occurrence of earthquakes. Its correlation with the other parameters of earthquake, such as the instrumentally measurable physical quantities like the ground particle velocity and acceleration, as well as the magnitudes of earthquakes, facilitate other means of evaluating earthquake hazards quantitatively.

In the conservative, but nevertheless realistic approach, the past observations of earthquake, define the model of future seismic activity. Earthquakes are assumed to behave randomly in space and time, yet these phenomena are as well observed to be related to tectonic structures and their movements. The relation between Seismicity and tectonics leads to the identification and delineation of seismo-genic source zones, which are utilized in the steps and procedures of seismic zoning studies. Nevertheless, the occurrences of earthquakes in seismic source zones are presumed to have uniform random distribution. Probably, a relatively realistic approach is to treat earthquakes as point sources, since the occurrences are non-uniform even for seemingly one geological unit (Ritsema, 1969). Due to randomness and non-uniformity in the earthquake occurrences and distribution, it is deemed appropriate to assess the level of destructive effects in terms of seismo-statistical methods in a site from cumulative/density distribution, that is known during the given observation period. The seismo-statistical methods provide information pertaining to probability of occurrence of selected level of effects, which is of seismic concern within a given interval of time. Some of the methods utilized are the Poisson probability distribution and the Bayesian approach of estimation.

The application of the Poissonian distribution in seismic hazard assessment studies in the Nubian-Arabian shield area can be seen in the works of (Thenhaus et al., 1986; Al-Haddad et al., 1994; Al-Amri et al., 2003). At present, the application of the Bayesian technique in seismic hazard analysis is not known to have been utilized in the Nubian-Arabian Peninsula. The Bayes method, however, have been studied and applied by others (Benjamin, 1969; Campbell, 1982, 1983; Ferraes, 1985; Papadopoulos, 1987; Staurakakis and Drakopoulos, 1995; Pisarenko et al., 1996) in seismic hazard mapping and as a contribution to the enhancement of the level of knowledge about seismic occurrences. The Bayesian formalism permits solution of problems, which otherwise cannot be done by the usual classical and other probability distributions of statistics. Hence, it seems appropriate and necessary to apply also the Bayesian method in conducting the seismic hazard analysis in the Afro-Arabian triple junction, as a comparative study and supplemental information about the earthquake occurrences and hazards in this area (Figure 1).

The seismo-volcanic activity in Afar depression is correlated to faulted zones of Wonji Fault Belt and the volcanic ranges of N. Loggia, Tat'Ali, Erta Ale and Alayta. The Wgnji Fault Belt is the axial rift zone of the Main Ethiopian Rift. The volcanic ranges in the depression are generated by basaltic fissures eruptions arranged in NW-SE and N-S directions. To the east of the depression and extreme west of the Gulf of Aden, the median valley of the Gulf of Tadjura is also marked with seismic activity. The deformational activities mostly occur around 11°N, 43°E. In January 22, 1929, a Ms = 6 earthquake occurred at around the western end of the Gulf of Aden. The maximum felt intensity at Djibouti is estimated to be VII-VIII. The tectonic activities in the Gulf of Tadjura may be attributed to the displacement of the Asal-Ghoubbat al Kharab graben in the northeasterly direction to the axial zone of the Gulf (Mohr, 1970). Some activities are also correlated to the deepest trenches of the Tadjura Gulf, which are bordered by normal faults oriented in the EW direction.

These are aligned by submarine volcanoes that are linked together by a set of NNE to NE faults, which displaced the axial trough of the Aden Gulf in the southward direction before reaching the Ghoubbat al Kharab (Mour, 1966). The tectonic structure in the Gulf of Tadjura can be interpreted as a westward extension of the transform fault system and expansion zone, which separates the African and Arabian plates.

Some of the seismo-volcanic activity in Afar Depression caused casualties and damage. In March 18 up to midsummer of 1627, seismo-volcanic activities in Aussa were reported to have destroyed all houses in Waraba in which 50 peoples were presumed to have lost their lives. In April 5, 1969, through magnitude (M_s = 6.1), the town of Sedro was completely destroyed, where 24 persons lost their lives and 167 were injured. In 1961, from the end of May until September, many earthquakes were recorded. The village of Majete was completely destroyed and in the nearby town Kara Kore, most masonry houses have been collapsed by magnitude M_s = 6.3 earthquake (Maamoun et al., 1981).

Seismicity released during lateral dike intrusions in the Manda Hararo–Dabbahu Rift (Afar, Ethiopia) provides indirect insight into the distribution and evolution of tensile stress along this magma assisted divergent plate boundary. In this paper, 5 dike intrusions among the 14 that form the 2005 to present rifting episode are analyzed with local and regional seismic data. During dike

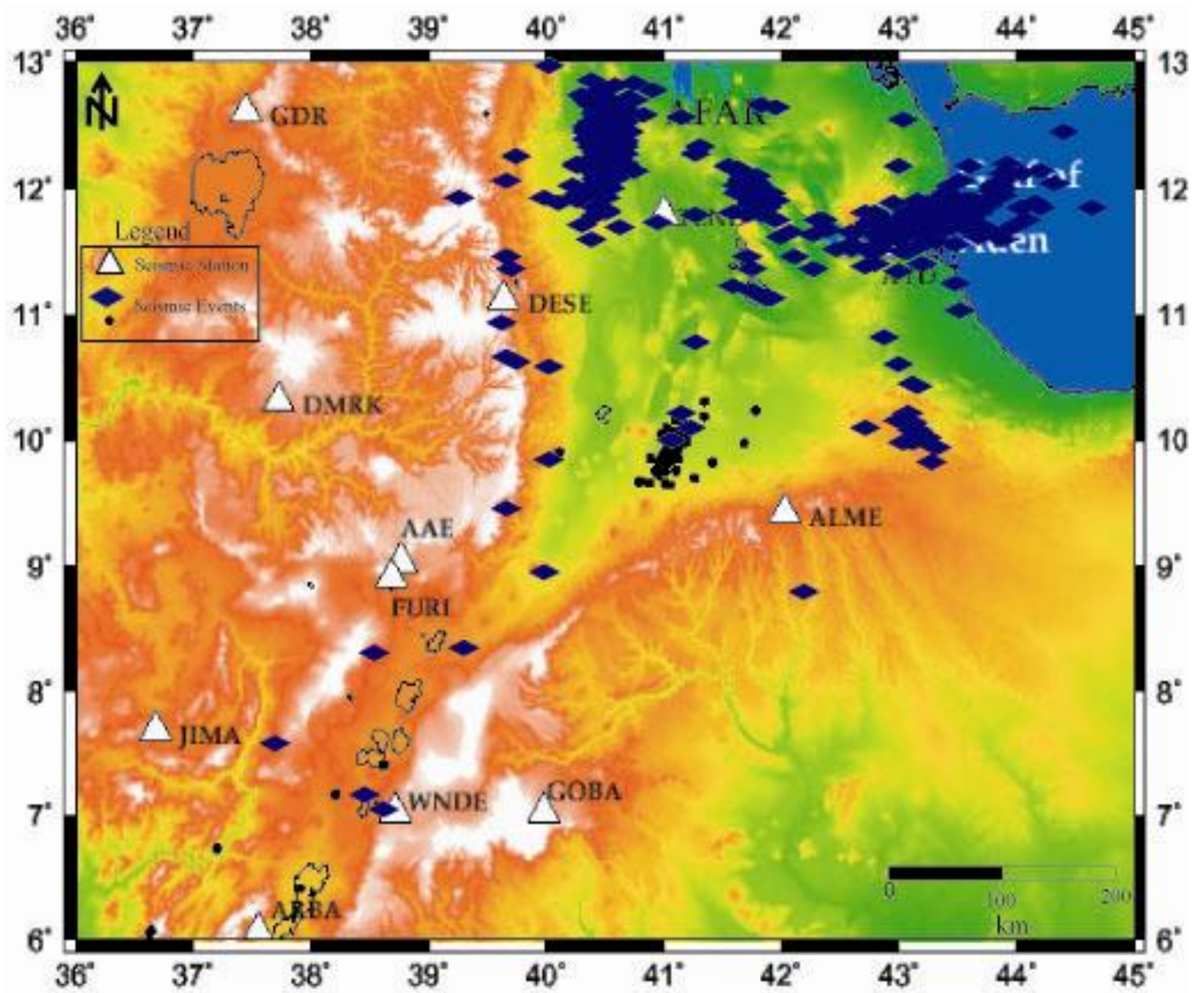

Figure 1. Showing the Digital elevation model (DEM) and seismicity of the study area.

intrusions, seismicity migrates over distances of 10–15 km at velocities of 0.5–3.0 km/h away from a single reservoir in the center of the rift segment, confirming the analogy with a slow spreading mid-ocean ridge segment. Comparison with geodetic data shows that the reservoir is located 7 km down rift from the topographic summit of the axial depression. Dikes emplaced toward the north are observed to migrate faster and to be more voluminous than those migrating southward, suggesting an asymmetry of tension in the brittle elastic lithosphere (Grandin et al., 2009; Grandin et al., 2010; Grandin et. al, 2011).

Seismicity during dike injections is concentrated near the propagating crack front. In contrast, faults and fissures in the subsurface appear to slip or open a seismically coeval with the intrusions. The seismic energy released during dike intrusions in the Manda Hararo Rift appears to be primarily modulated by the local magnitude of differential tensile stress and marginally by the rate of stress change induced by the intrusion. The low level of seismic energy accompanying dike intrusions, despite their significant volumes, is likely an indicator of an overall low level of tension in the lithosphere of this nascent plate boundary (Grandin et al., 2009; Grandin et al., 2010; Grandin et. al, 2011).

The past and recent seismo-volcanic activities in Afar Depression, that caused casualties and damage to properties, are indicative of a geologically hazardous area. The geologic hazards are expected to recur in the future in the area relative to the plate movements at the triple junction, which caused RRR motions. Afar triple junction has been studied on the light of the early development of magmatic margins, where respective arms of the triple junction are generated at different stages/rates of the break-up process. The flood basaltic magmatism, which caused the older separation of Arabia from Africa, is widely separated in time from the younger opening of the Main Ethiopian Rift that makes the incipient Nubia-Somalia plate boundary. Thus, Afar triple junction is not a primary feature of the break-up, but as a consequence of the Afar mantle plume (Wolfenden, 2004; Hofstetter and Beyth, 2003; Camp and Roobol, 1992).

METHODOLOGY

Ambraseys' catalogue (1988), describing the seismicity of Saudi Arabia and adjacent areas from the year 2150 BC up to 1964 AD, was found to be a comprehensive compilation of the southern Afro-Arabian triple junction earthquake events, and we selected this catalogue as a data source for historical earthquake events and their effects for the period.

The installation and operation of the World Wide Standardized Seismograph Network (WWSSN) of the United States Geological Survey (USGS) in 1964 has contributed immensely in the monitoring and compilation of earthquake events in the study area. The USGS findings and compilations published as seismic bulletins (PDE and EDR) were used as a source of earthquake data from 1965 to 2002.

The bulk of the magnitude data in the USGS seismic bulletins is expressed in terms of the body-wave magnitude (M_b). For this reason and the fact that the magnitude values are determined from sets of standardized seismographs, the preferred utilized magnitude in this study is the M_b. Local and duration magnitudes given in the data sources are assumed to be equivalent to the M_b since it is presumed that in their calibration, the M_b is utilized as the standard magnitude scale. Other magnitude scales that confirms with the equations utilized in the methodology are retained. We note that the body wave magnitudes are consistent below the 6.5 level. Since, there are only few events above the 6.5 value, it is appropriate then to employ the M_b, as the preferred scale in the study.

The Bayesian approach to statistical methods of estimation combines sample information with other available pertinent prior information. The sample information is a joint probability distribution of random variables, while the prior information is normally a priori probability distribution of one of the parameters whose value is sought for the population of the random sample from which it is selected.

Earthquake occurrence in time t_1, $t_2 \ldots t_n$ in the area of study is assumed to follow the Poisson probability distribution, P (n, t/h), which is:

$$P(n,t/h) = \frac{(ht)^n e^{-ht}}{n!} \quad (1)$$

Where n is the number of events occurring in time interval, t and h is the mean rate of occurrence in t. Suppose, in a region of the study area, it is observed that, n_o, are the events occurring in time, t_o, which is the observation period. Then, the probability of the specific outcome from Equation (1) is exhibited as:

$$G(h) = P(n_0, t_0 / h) = \frac{(ht_0)^{n0} e^{-ht_0}}{n_0!} \quad (2)$$

which is a function of the mean rate of occurrence. From Bayes theorem, its joint probability distribution is expressed as follows:

$$P(h) = a * F(h) * G(h) \quad (3)$$

where: F(h) is the prior distribution of h, which is assumed to be uniform, and a is a constant, such that the integration from limits (o, ∞) gives:

$$\int P(h)\partial h = \int a * F(h) * G(h) * \partial h = 1 \quad (4)$$

From Equation (4), a F(h) can be considered as a normalizing constant, that is normalized for aF(h) = t_o, so that Equation (3) can be re-written as:

$$P(h) = a * F(h) * G(h) = \frac{t_0[(ht_0)^{n0} e^{-ht0}]}{n_o!} \quad (5)$$

This considers the posterior probability of n events occurring in the time t years. This will be the probability P(n, t/h) weighted with regards to P(h), that is:

$$H(n,t) = \int P(n,ht) * P(h) = \int \frac{(ht)^n e^{-ht}}{n!} * t_0 * \frac{(ht_0)^{n0} e^{-ht0}}{n_0!} * \partial h \quad (6)$$

From Benjamin (1968), the integral of Equation (6), whose limits are (o, ∞), yield:

$$H(n,t) = \frac{(n+n_0)!}{n! n_0!} * \frac{(t/t_0)^n}{[(1+(t/t_0)^{n+n0+1})]} \quad (7)$$

When no events of threshold intensity I_i occur in t years, Equation (7) becomes:

$$H(n,t) = \frac{1}{(1+t/t_0)^{n0+1}} \quad (8)$$

However, if at least one event, $I \geq I_i$, occurs in t years, then the probability of occurrence/ exceedance is as follows:

$$H(n,t) = 1 - \frac{1}{(1+t/t_0)^{n0+1}} \quad (9)$$

Equation (9) is applied in the study area for intensities VI and VII according to the Medvedev-Sponheuer-Karnik (MSK) intensity scale (1964) for t = 100 years.

The study area extends from 10 to 14°N and from 30 to 48°E (Figure 1). This range is subdivided into half (0.5) degrees latitude and longitude that served as grid points. At every grid point, each earthquake event affecting the respective grid is calculated for I_i = VI and I_i = VII using the following equations:

$$I = I_o - 1.8 \log (r / h) - 0.018 (r-h) \quad (10)$$

$$M_s = 0.65 I_o + 2.2 \log h - 1.3 \quad (11)$$

$$M_s = 1.07 M_b - 0.48 \quad (12)$$

$$r^2 = D^2 + h^2 \quad (13)$$

Where: I is the intensity at the hypocentral (r) and epicentral (D) distances in kms, I_o is the intensity at the epicenter in the MSK, while M_s and M_b are the surface-wave and body-wave magnitudes, respectively, and h is the focal depth. Equations (10 and 11) and (12) are defined empirically by Punsalan and Al-Amri (2003) and Al-Amri (1994), respectively from the local seismic data. The class

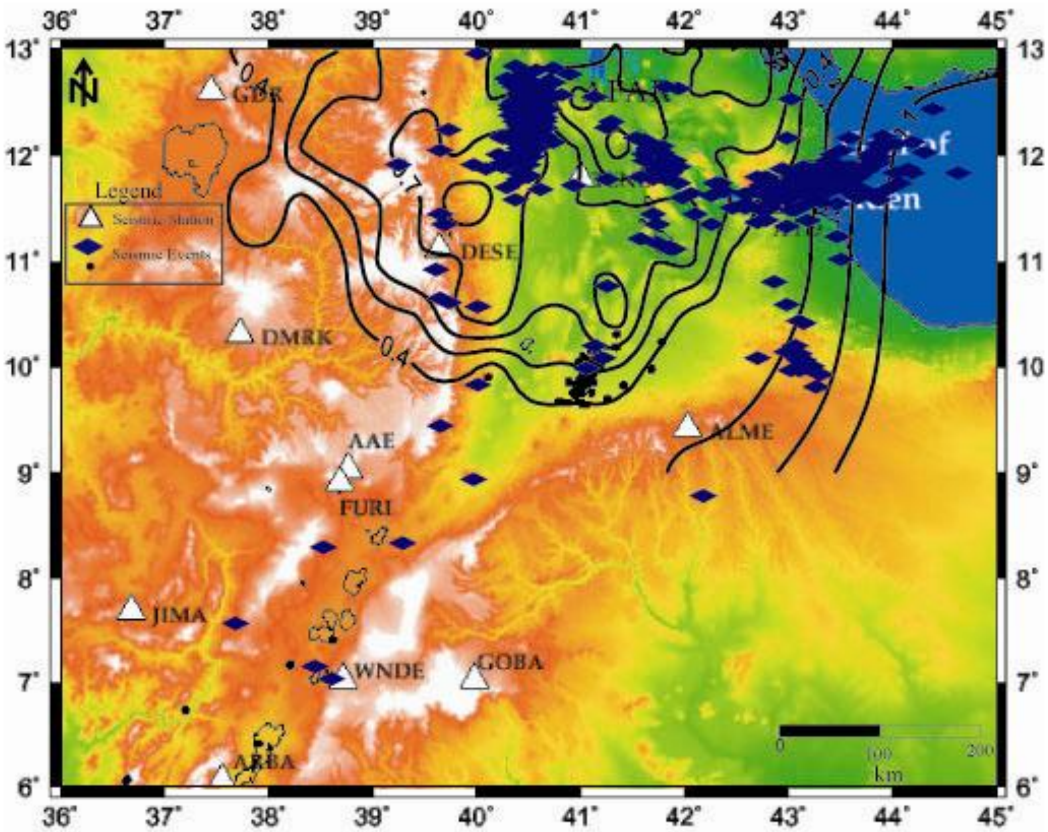

Figure 2. Map of the spatial distribution of the probability of exceedance for the intensity VI (MSK) in the next 100 years as obtained from application of bayes theorem in the study area for the time independent probability distribution.

range of I, as calculated from Equation (10), is $0.4 + I_i > I > I_i - 0.5$; where I_i is the center of the class as inferred from the MSK intensity scale.

The intention of subdividing the study area into half-degree latitude and longitude is due to scarcity of magnitude data, especially for the stronger events. Thus, this procedure and the utilization of the earthquake events as point sources for the free zone technique of seismic assessment provide wider and detailed realistic coverage for the earthquake effects of intensities VI and VII. These levels of intensity are selected, since these ranges can cause moderate to total collapse of many pre-fabricated to half-timbered structures, allowing ground motion dependence on the medium properties. It is also expected that, the procedure and the data treatment lead to generation of sufficient data for intensities VI and VII.

RESULTS AND DISCUSSION

The results of the present study are shown in Figures 2 and 3. The figures indicate the probability of occurrence/exceedance for intensities VI and VII in the MSK intensity scale in a time interval of 100 years. In Figure 2, it is shown that, the highest probability of occurrence for intensity VI is around 80%. These are approximately located at 11.43°N, 41°E, 12.5°N, 42.5°E, and 12°N, 43°E. The axes of orientation and expansion of the spatial distribution of the probability iso-curves are in the NE and NW directions. Likewise, the highest probability of exceedance for intensity VII (Figure 3) is about 48%. These are estimated to be located at 10.5°N, 40°E, 11°N, 41°E, 12.5°N, 41.5°E and 12.5°N, 42.5°E. The distribution and expansion of the probability iso-curves are approximately aligned in the NE and EW directions too. The spatial distribution of the probability iso-curves are in conformity with the seismo-volcanic activities in Afar Depression, due to the mega-scale accommodation zones in the early and recent continental break-up boundary of the Afro-Arabian plateau in Ethiopia. Motions along these mega-scale accommodation zones enabled the different arms of Afar RRR (rift-rift-rift) triple junction to join together (Thesfaye et al., 2003). Two of the three arms of the rift system, the southern Red Sea Rift and the Main Ethiopian Rift came in direct contact in Central Afar. The tectonically active part of the third arm, which is the Gulf of Aden Rift failed to join completely the other two rifts at the eastern part of Central Afar. For this reason, a broad zone of active extensional deformation is taking place in Central Afar, which is one of the three sections (northern, central and

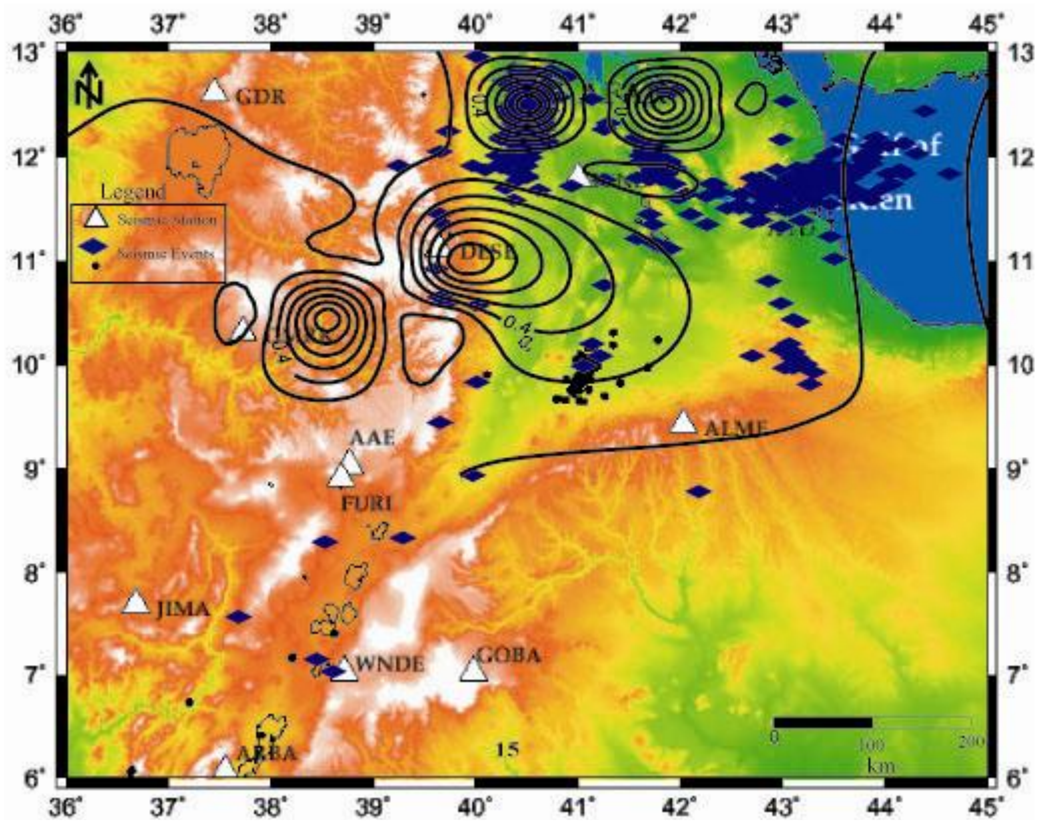

Figure 3. Map of the spatial distribution of the probability of exceedance for the intensity VII (MSK) in the next 100 years as obtained from application of bayes theorem in the study area for the time independent probability distribution.

southern) of the Depression.

Conclusions

In summary, Afar triple junction is a geologically hazardous area because the junction represent a younger tectonic region that is characterized by the break-up of rigid crustal structures. According to ideas and studies made (Mogi, 1962; Miyamura, 1962; Al-Amri et al., 1998), there is a high expectancy for earthquake of large magnitudes to occur in the future. These conceptions are matched with the findings in this study, which show the probabilities of occurrence for intensities VI and VII. The documented reports of destruction are like-wise other manifestation of the existing hazards. Thus, it is necessary that detailed seismic hazard mapping in the junction is required to be done in the junction to provide information regarding future occurrences of earthquakes and the probable identification and delineation of seismic source zones. Conservative estimates in the values obtained in the results are expected because of inadequacy in the data, which cannot be avoided. However, the results show that the Bayesian technique when applied in seismic hazard analysis provides a means of obtaining supplementary information in addition to the primary importance in earthquake disaster mitigation. Uncertainties too are usually encountered due to the scattering of data in the conversion relations of earthquake parameters, insufficiency of appropriate seismic instrumentation and local ground conditions.

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