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Magnitude Calibration of the Seismographic Sub-network in NW Saudi Arabia

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Abstract. Two magnitude formulas to be applied in seismic parameter determinations were developed for the seismographic sub-network in NW Saudi Arabia: ML = Log (A / T) + 3.4 Log D + 2.55 and Mc = 2.55 Log (t) - 2.15. These formulas were empirically determined through magnitude calibration of the amplitude and total trace duration data from the seismic stations of the network. The relationship found between coda magnitude (Mc), duration, and distance indicates negligible correction factor for epicentral distance of earthquake events less than 1000 km from the network making it compatible to use with the adapted local magnitude scale (ML) for better estimate of earthquake magnitude values. These findings make the two magnitude scales supplementary to each other and their complimentary roles could possibly cover a wider area in the observation of earthquake events in the eastern Mediterranean region. Both magnitude scales give good fits with standard error of 0.16 for ML and 0.12 for Mc. Other useful relations were also empirically determined between corresponding calculated values from the two magnitude scales and the observed body-wave magnitude values. These were: ML = 0.91 mb + 0.39 and Mc = 0.89 mb + 0.48 which can be applied for counter-checking and verifications of calculations when either one is known.

Introduction

In the statistical study of earthquakes, it is desirable to have a scale for rating the earthquake size in terms of their original energy independent from effects generated at any particular point of observation. This rating scale is known as magnitude of an earthquake. The first magnitude scale was defined by Richter [1] for the classification of the California earthquakes. This scale was called local magnitude. Other magnitude scales are defined in accordance with the types of the seismic waves from which these are taken. These are the body-wave magnitude from the body waves and surface-wave magnitude from the surface waves.

Ever since the introduction of the magnitude and its extension from the original definition to different areas, types of seismic instrumentation, and different depths of foci, it became the most important number characteristics of earthquakes. The relation of magnitude to earthquake energy released from the focus has been a tool to evaluate forces involved in orogenic processes, comparing seismic activities between different areas during the same interval of time, and the energy balance of earthquake dynamics. Likewise, magnitude values provide the simplicity in handling earthquake data in the catalogue form for use in seismological studies pertaining to seismicity studies and dissemination of information.

The steady development and improvement of seismological instrumentation and theories in focal processes and seismic wave propagation have brought about other changes on the magnitude scales. These are the seismic moment and duration magnitude from coda wave. With the advent of computerized local earthquake analysis, new method of magnitude determination for local earthquakes became possible. Recordings of strong and larger scale earthquakes and near seismic events can exceed the linear range of the recording system and therefore limit the usefulness of scale based in using the amplitude. In this case, using the duration of coda wave was taken to be preferable.

Magnitude scales are affected by the types of seismic instrumentation, scattering, geometrical spreading due to the vertical and horizontal heterogeneity of the earth's crustal structure. Due to these factors, it became necessary to respect the regional and instrumental differences. From standard magnitude values taken from internationally accepted magnitude formulas, different institutions calibrate their own magnitude scales for their own use for seismological researches pertaining to their respective areas. The most important in an earthquake prone country is the development of its capabilities to mitigate earthquake disaster as reflected by its plans and programs in seismological activities.

One contributory step is in the estimation of the sizes of seismic events. The size of an event is related to the earthquake hazards it generates. Timely dissemination of earthquake information and related seismic parameters could probably minimize the adverse effects of the generated earthquake hazards. Provided with an earlier earthquake information, concerned disaster and relief agencies can react immediately and implement the appropriate disaster preparedness plan. This can be done if the necessary and essential formulas in earthquake observation have been previously developed and established.

Hence, the purpose and intent of this study is to undertake the preliminary steps in developing magnitude formulas for the Aqabah sub-network which is located in the most seismically active part of Saudi Arabia.

Data and Materials

The seismographic sub-network of the Seismic Studies Center (SSC) of King Saud University (Fig. 1) consists of eight stations in NW Saudi Arabia, namely, Haql (HQL), Ouyannah (AYN), Sharaf (SHRF), Sultana (SALT), Birmashi (BMSH), Bada (BADA),

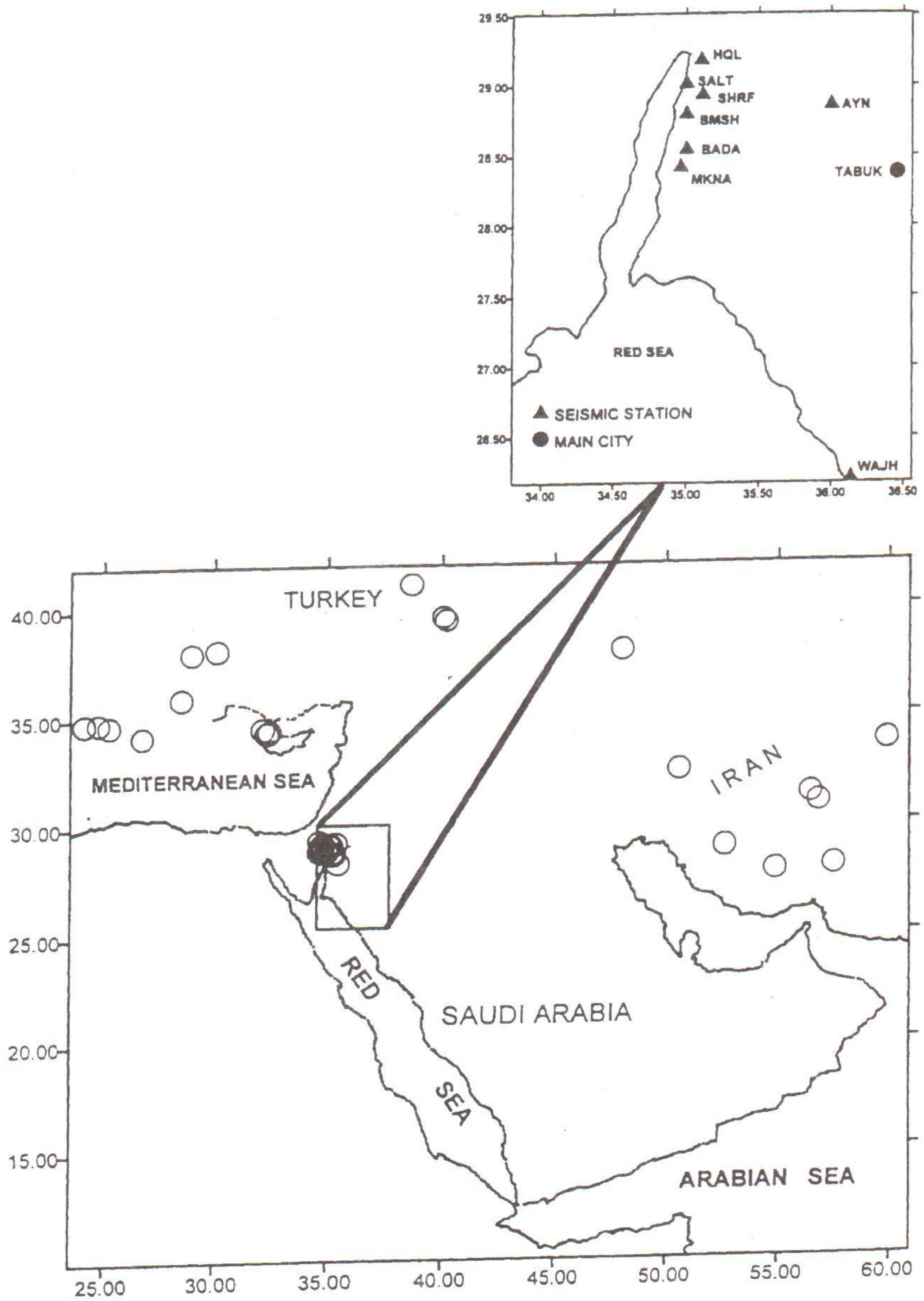

Fig. 1. Location map showing seismic stations of the Aqabah sub-network and epicentral data used in this study.

Makna (MKNA) and Wajh (WAJH). The seismometers of these stations are composed of Teledyne Geotech S-13 short-period vertical, whose free period is approximately 1 sec. The Aqabah sub-network has recently been standardized. The bandpass range is: high pass band (0.8 Hz), low pass band (5 Hz) and peak magnification at around 4 Hz (Fig. 2).

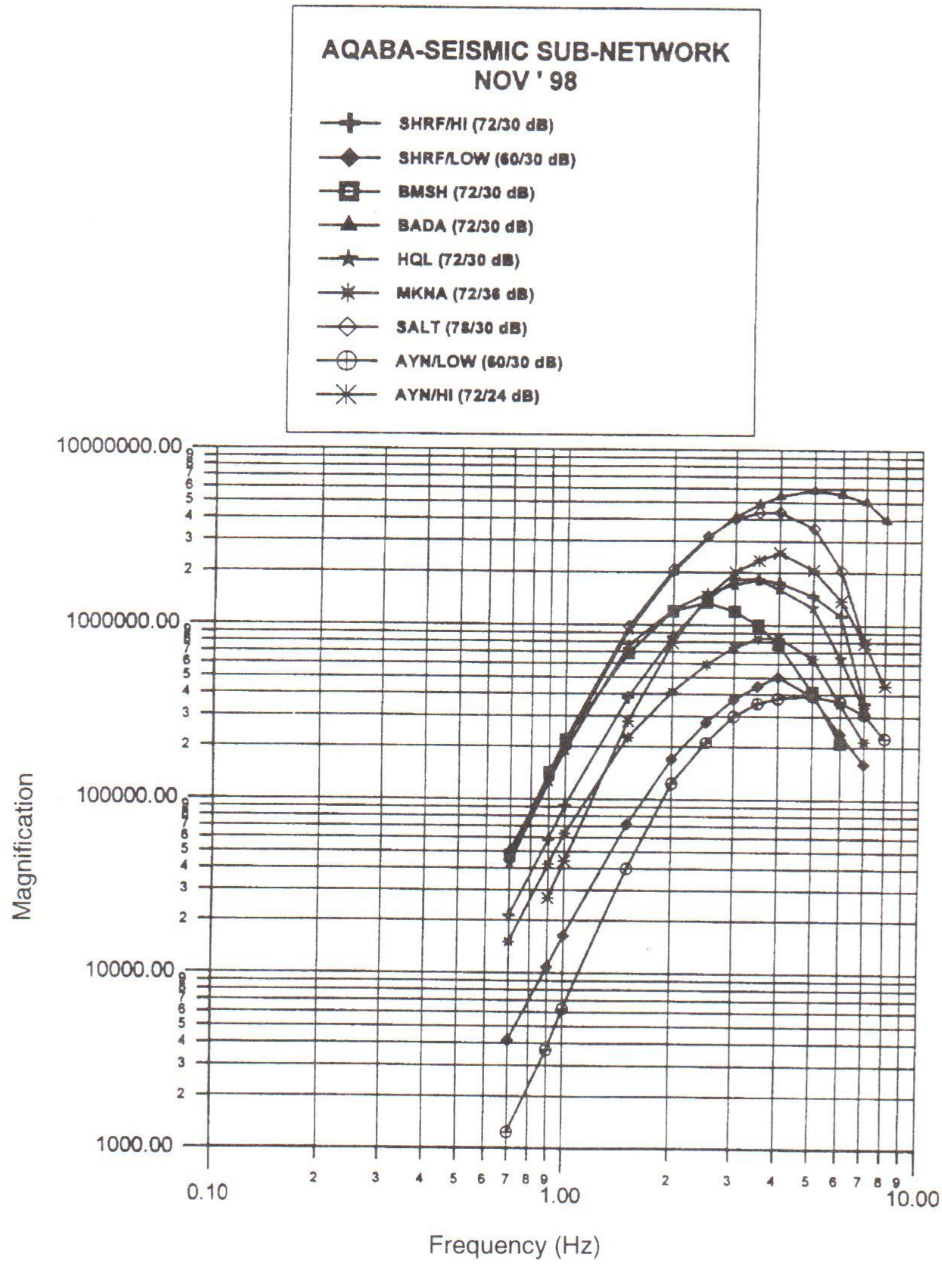

Fig. 2. Analog system response curves for eight short-period seismic stations of the Aqabah sub-network in NW Saudi Arabia.

To develop the magnitude scales for the Aqabah sub-network, a set of body-wave magnitude (mb) data were selected and compiled from the Saudi Arabian Earthquake Database (SAED) and Preliminary Determination of Epicenters (PDE) of the United States Geological Survey for the period 1995 - 1997 from earthquakes originating from the eastern Mediterranean region, Gulf of Aqabah and Iran (Fig. 1). Entries in SAED were cross-checked and additions were made from various sources of earthquake records to ensure that repetitions are not included in this analysis.

Corresponding to the set of compiled magnitude data, sustained maximum double amplitude from the analog recordings and oscillation durations from the sub-network seismic stations were read. The total oscillation duration is measured from the initial onset of the first P- wave arrival up to the point where the amplitude signal is approximately twice the noise level. There were two different sets of data that were collated and compiled. These were 34 sustained maximum double amplitude and 56 duration data measured from the sub-network ranging from a distance of 400 - 1200 km and 40 - 600 km, respectively. Range of magnitude values is from 3.5 to 5.4.

Magnitude Calibration

The magnitude formulation for the Gulf of Aqabah follows the practical procedure of applying regression analysis techniques in calibrating magnitude scale when sufficient number of magnitude standard values are considered. From the set of data collected for the Aqabah sub-network, two types of magnitude scale were intended to be developed. These are the adapted local and coda magnitudes.

A. Local magnitude (ML)

The local magnitude scale was formulated by Richter [1] as:

$$ML = \text{Log } A - \text{Log } Ao \qquad (1)$$

where Log A is the decadic logarithm of the vectorial sum of the horizontal trace amplitude from zero to peak in mm at an epicentral distance (D), and Log Ao is the calibrating function for a magnitude zero event at a specified epicentral distance. The calibrating function is generally taken as:

$$- \text{Log } Ao = a \text{ Log } D + b D \qquad (2)$$

from the assumption of parallelism that is fitted to the observed amplitude decay curve [1], where a is the attenuation factor of D, (b/log(e)) is the seismic absorption coefficient, and e the base of natural logarithm. Usually, the seismic absorption coefficient is negligible so that equation (2) can be re-written approximately as:

$$- \text{Log } Ao = a \text{ Log } D + c \qquad (3)$$

From (1) and (3) gives

$$ML - \text{Log } A = a \text{ Log } D + c \qquad (4)$$

The local magnitude scale was particularly developed from the specific type of instrument (Wood-Anderson) and for the California earthquakes whose depths of foci are within 15 km. For development and application of the local magnitude scale at different places and to different depths of foci and epicentral distances, and different types of seismic instruments, the body wave magnitude scale (mb) was introduced by Gutenberg [2] which is given as:

$$mb = \text{Log}(A / T) + Q(D,h) \tag{5}$$

where T is the period of the wave of the maximum ground amplitude (A) (0-peak) in micrometer of the vertical component, and Q is the calibrating function dependent on D and depth (h). The term (A / T) opens the possibility of the local magnitude scale for application at different seismological agencies. Re-writing (5) gives

$$mb - \text{Log}(A / T) = Q(D, h) \tag{6}$$

Since (5) is just an extension of (4), substitution of the values of mb in (4) is permissible as an approximation, so that,

$$mb - \text{Log}(A / T) = a \,\text{Log}\, D + c \tag{7}$$

In (7), the set of corresponding mb and D data could be substituted, and by means of multiple regression techniques the constants can be determined to yield the required adapted local magnitude scale formula (ML) calibrated in terms of mb for the Aqabah sub-network which is

$$ML = \text{Log}(A / T) + 3.4 \,\text{Log}\, D + 2.55 + Ki \tag{8}$$

where Ki is the mean station correction of the ith station and the epicentral distance D is in unit of degrees. The mean station correction is determined from the average of the differences between the calculated (7) and observed (mb) magnitudes for each station of the sub-network.

To determine the original local magnitude (ML) for the sub-network, the A values have to be normalized [3] to the distance of 100 km to conform with Richter [1] local scale, that is,

$$ML = \text{Log}\, A + 3.4 \,\text{Log}(111.2\, D / 100) + \text{Log}((Iwa(T) / I(T)) \tag{9}$$

where Iwa and I are the Wood-Anderson and Aqabah sub-network seismographs magnifications corresponding to period T. However, for the present, equation (8) can be assumed to be the adapted local magnitude scale of the Aqabah sub-network due to the unavailability of Iwa and by presuming that c is approximately equal to the term - 3.4

Log (100/111.2) + log (Iwa(T)) when the corresponding values of ML and mb do not differ significantly. Other useful relation which can also be empirically determined from the corresponding calculated (8) excluding Ki and observed magnitude values is in the form

$$ML = b\,mb + k \qquad (10)$$

where b and k are constants. The least square estimate gave

$$ML = 0.91\,mb + 0.39 \qquad (11)$$

B. Coda magnitude (Mc)

The assumption of parallelism does not fit the amplitude decay curve at near distances [4]. Likewise, strong and larger earthquake events may exceed the linear range of seismic recordings [5]. For earthquakes wherein the amplitude of the recorded wave cannot be used due to these factors, another set of formula is required and needed to be developed. A linear relation has been consistently observed between oscillations duration and magnitude of events [6, 7, 8, 9]. This is given as

$$Mc = e\,Log\,(t) + f\,D + g \qquad (12)$$

where Mc is the coda magnitude, (t) is the total duration of oscillations in seconds, D is the epicentral distance, e, f, g are constants. The dependence on the epicentral distance is always small for distances less than 200 km [6, 10] so that (12) could be re-written as

$$Mc = e\,Log\,(t) + g \qquad (13)$$

Calibration of (12) and (13) through substitution of the corresponding compiled data of mb, D and t and applying multiple regression techniques, the constants e, f and g can be determined which gave the empirical relation:

$$Mc = 2.55\,Log\,(t) + 0.118\,D - 2.21 \qquad (14)$$

where the epicentral distance is in degrees. When D is not considered, (13) becomes

$$Mc = 2.55\,Log\,(t) - 2.15 + Ci \qquad (15)$$

where Ci is the mean station correction of the ith station. Similarly, applying the same procedure as done for ML and mb to the corresponding calculated (15) and observed mb values yields an empirical relation which is,

$$Mc = 0.89\,mb + 0.47 \qquad (16)$$

Discussion and Interpretation

The plotted values for equations (7) and (10) are shown in Figs. 3 and 4, respectively. The application of regression techniques to Fig. 3 yields the regression values for a = 3.4, c = 2.55, with standard error (S.E.) = 0.16, and squared correlation coefficient (R) = 0.9. The relation between the calculated (8) excluding Ki and observed mb values as shown in Fig. 4 was 0.91 for the coefficient and 0.39 for the constants with S.E.= 0.15 and R = 0 .91.

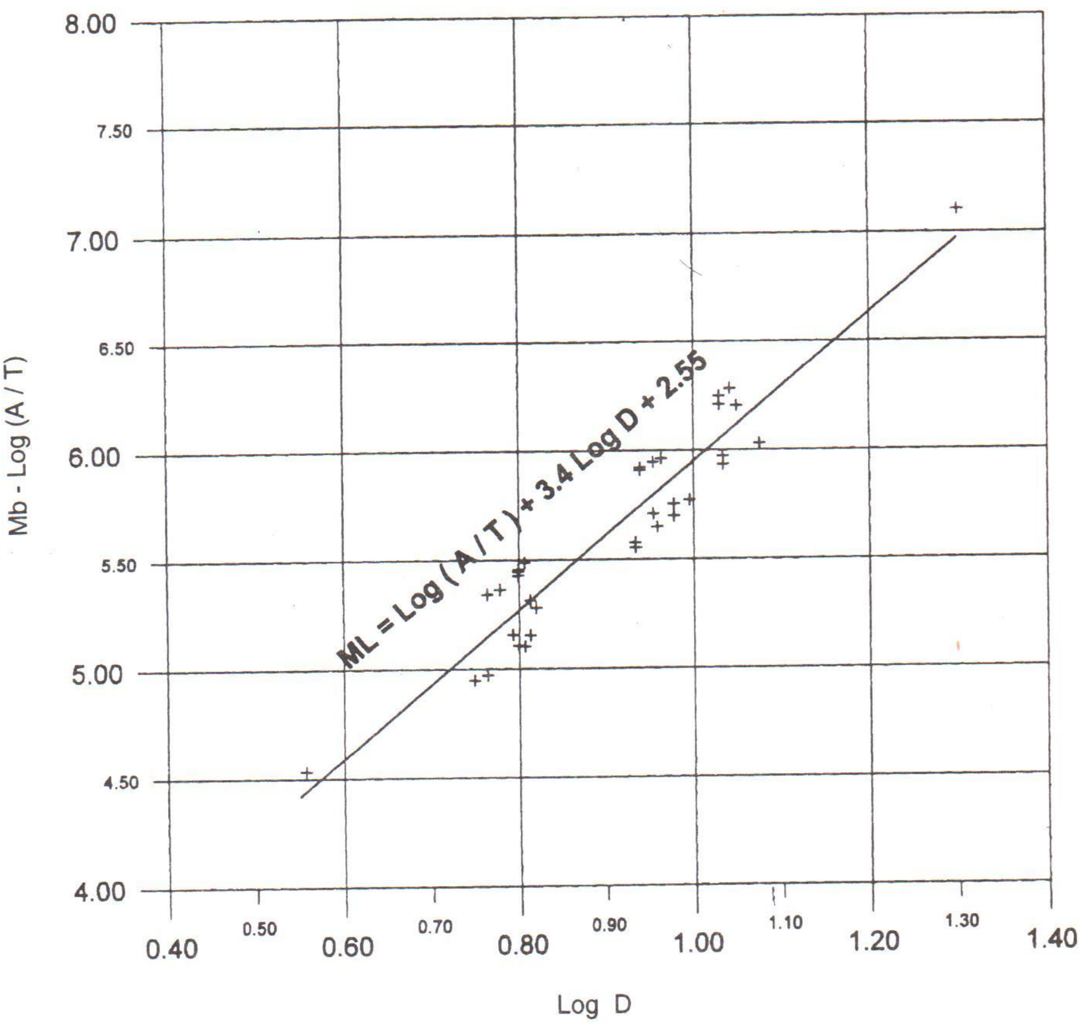

Fig. 3. Plotted data used in determining the adopted local magnitude scale (ML). The vertical axis represents the difference values between the body-wave magnitude (mb) and the corresponding logarithm of amplitudes (A/T) in micrometer. Abscissa is the logarithm of the corresponding epicentral distance (D) in degrees.

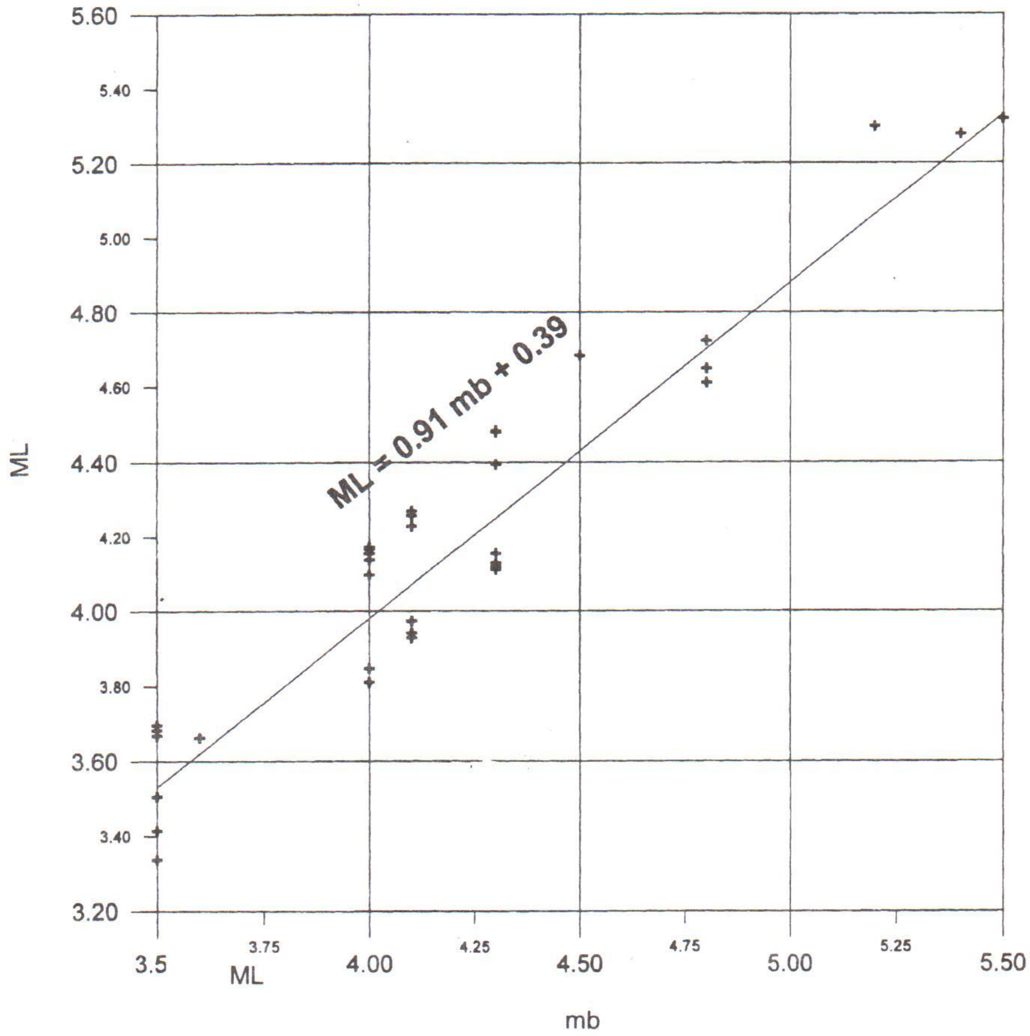

Fig. 4. Plottings of corresponding calculated local magnitude (ML) and observed body-wave magnitude (mb) values used in determining the empirical relation. Vertical axis is ML and horizontal axis is mb.

Body wave magnitudes are consistently based on the maximum (A / T) referred to ground motion. Main differences on the mb values are due to incomplete agreement about instrument response and the amplitudes to be used. Observational data such as the amplitudes and durations automatically include both geometrical spreading and seismic absorption. From observations, the amplitude attenuation is mainly determined from geometrical spreading with less influence of absorption. With the use of body magnitude data from the USGS, the geometrical spreading is taken care of to give better estimate in the determination of the attenuation factor. USGS routine function applies Gutenberg and Richter [11] calibrating values dependent on D and h in magnitude determination.

The mb values from USGS are obtained from the mean average of sufficient determination and does not reflect the anomalous values. Hence, the minimal scatter of the plotted corresponding data in the determinations of empirical relations in this study could be attributed to some reading errors and probably to some lesser dependence on wide range of local factors such as lateral and vertical heterogeneity of the geological structures in the region which probably affect the attenuation of the amplitude. Partly, the scattering in Fig. 3 at about epicentral distances from 5 - 10 degrees may also be due to the observed global oscillations of the calibrating function due to geometrical spreading as prepared in the forms of graphs by Nortmann and Duda [12], and Gutenberg and Richter [11]. The absorption coefficient changes with the period of the waves, increasing with decreasing period and for this reason makes it appropriate to use the velocity (A/T) for magnitude determination [13]. Likewise, the body wave magnitude is a rating of radiation energy at variable periods and is based on observation from seismographs systems having unknown bandwidths. This constitutes to its numerical instability if determined from several seismic stations. Only body wave magnitude determined from seismograph system with the same bandwidth are eventually free from bias due to variable bandwidth according to Nortmann and Duda [12]. In agreement with this argument, the Aqabah sub-network was selected for the initial development of the SSC magnitude formulas due to its standardized seismic network. Therefore, the obtained attenuation factor in this study could possibly reflect nearer estimate to the real attenuation value in this area.

Because of the unknown bandwidths of different regional network, a comparative discussions of the different empirical magnitude formulas obtained respectively by regional network is insignificant. Moreover, in global scale, the calibrating function may be derived from global and anelasticity models which requires further studies and constitute data compilation from digital recordings from instruments with broad bandwidths.

An attempt to determine the seismic absorption coefficient was also undertaken. This was done in two steps. The first step was to sort the difference values (mb - Log A/T - a Log D) with that of the corresponding distances (D). The sorting was arranged in the ascending order with D as the reference. The sorting that gives a linear relation was selected and through application of regression analysis the constants were determined. The obtained mean values were 0.086 / degree for the absorption and - 0.7 for the constant. The accuracy of these values are, however, relatively unreliable due to limited data.

For application and better estimate of magnitude values of earthquake events from the adapted local magnitude scale for the Aqabah sub-network in any of its seismic stations for earthquake events from range 2 - 20 degree epicentral distance, mean station corrections were evaluated. The mean station corrections are as follows: BADA = 0.022, HQL = - 0.12, AYN = 0.17, MKNA= 0.12 and SALT = 0.17.

The application of linear regression analysis in Fig. 5 gave the regression values for: e = 2.55, g = - 2.15, S.E. = 0.12 and R = 0.89. Multiple regression analysis performed to the three observed values (mb, t and D) gave the distance correction factor which is 0.018 / degree which is insignificantly small value even at 1000 km epicentral distance. For this relation (12), the e = 2.55, f = 0.018, g = - 2.21, S.E. = 0.11 and R = 0.91. The high correlation coefficients reflect minimal scatter of the plotted data which could be attributed probably to proper implementation of the guidelines for reading and interpretation. Some authors [1,7] include higher terms of the decadic logarithm of the duration from theoretical considerations and observations. However, the higher term in this study does not appear in the graph of magnitude and duration to warrant its inclusion and analysis. Probably this linearity could be attributed to the confinement of the compiled data to moderate events and distances below 6 degrees.

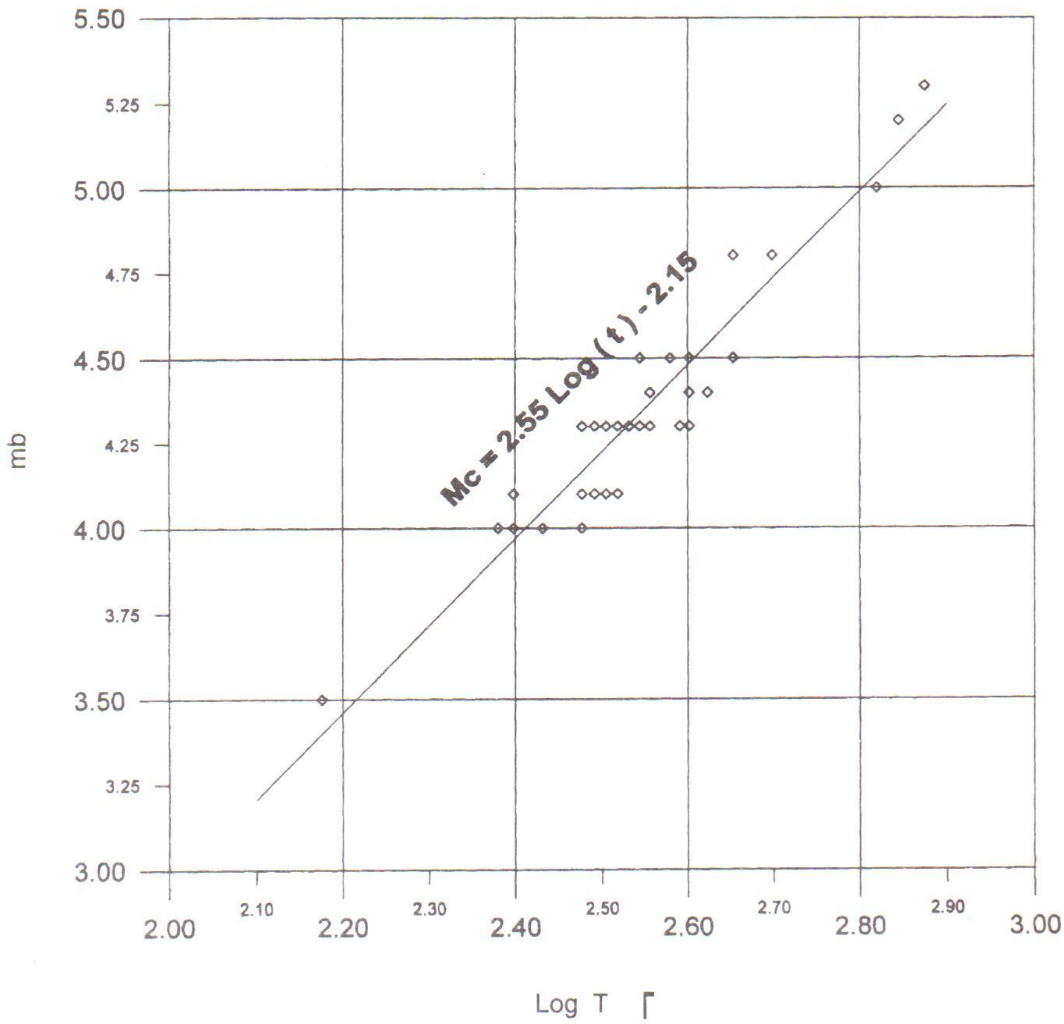

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Fig. 5. Plotted data used in determining the coda magnitude relation (Mc). The vertical axis shows the values of body-wave magnitude (mb) and the abscissa is the decadic logarithm of the corresponding duration (T) in seconds.

The minimal scatter of the plotted corresponding data is seen to be concentrated from magnitude 4 - 4.5 and t is from 330 - 450 sec. At these values, the corresponding distance range from 3 - 6 degrees epicentral distance. Probably, aside from the effects of the heterogeneities and probable errors on the magnitude determination, the scatter could also be attributed to the presence of dislocations such as transform and land faults and geophysical phenomena such as high heat flow and magnetic anomalies traversing the paths of the waves particularly along the two Gulfs (Aqabah and Suez) and the Red Sea. It is also probable that the factors affecting the amplitude attenuation also influence the seismic trace duration.

Even up to the range of 1000 km epicentral distance, the effect of the distance correction factor can be considered negligible compared to an error of 0.3 magnitude unit due to inaccurate reading of the duration [6]. Hence, for the coda magnitude scale the second relation (eq. 13) can be used as an alternate formula for magnitude calculations. Likewise, a useful relation could be empirically determined from the corresponding calculated (13) excluding station correction and observed magnitude (mb) values. The graph for this relation is shown in Fig. 6. The relation found gave the regression coefficient for the mb to be 0.89 and the constant is 0.48, with S.E.= 0.11.

Same as in the case of the amplitude - magnitude relation, mean station corrections were likewise determined for the Aqabah sub-network. The mean station corrections were evaluated for better estimate of magnitude from application of the coda magnitude formula. The mean station corrections are as follows: BADA = 0.02, HQL = - 0.032, SALT = 0.01, AYN = - 0.03, MKNA = 0.012, WAJH = 0.04 and BMSH = - 0.11.

Owing to scarcity of data due to elimination of some station readings which could be attributed to component malfunctioning and to insufficient number of testing for the recently empirically developed magnitude formulas for the Gulf of Aqabah, undertakings for further modification from additional data and test are reserved.

A significant correlation that is observed between the two empirically determined magnitude scales is the condition that each supplements the other. For the coda magnitude, the distance correction is negligible for epicentral distance even up to a distance of 1000 km which can serve as an alternate formula for saturated amplitude for the adapted local magnitude scale or vice-versa for successive events. This complimentary role assumed by the two scales of magnitude can contribute to observation of earthquake events over a wider area of coverage. Nevertheless, additional data and test of the two magnitude scales is necessary for further investigation and conclusion.

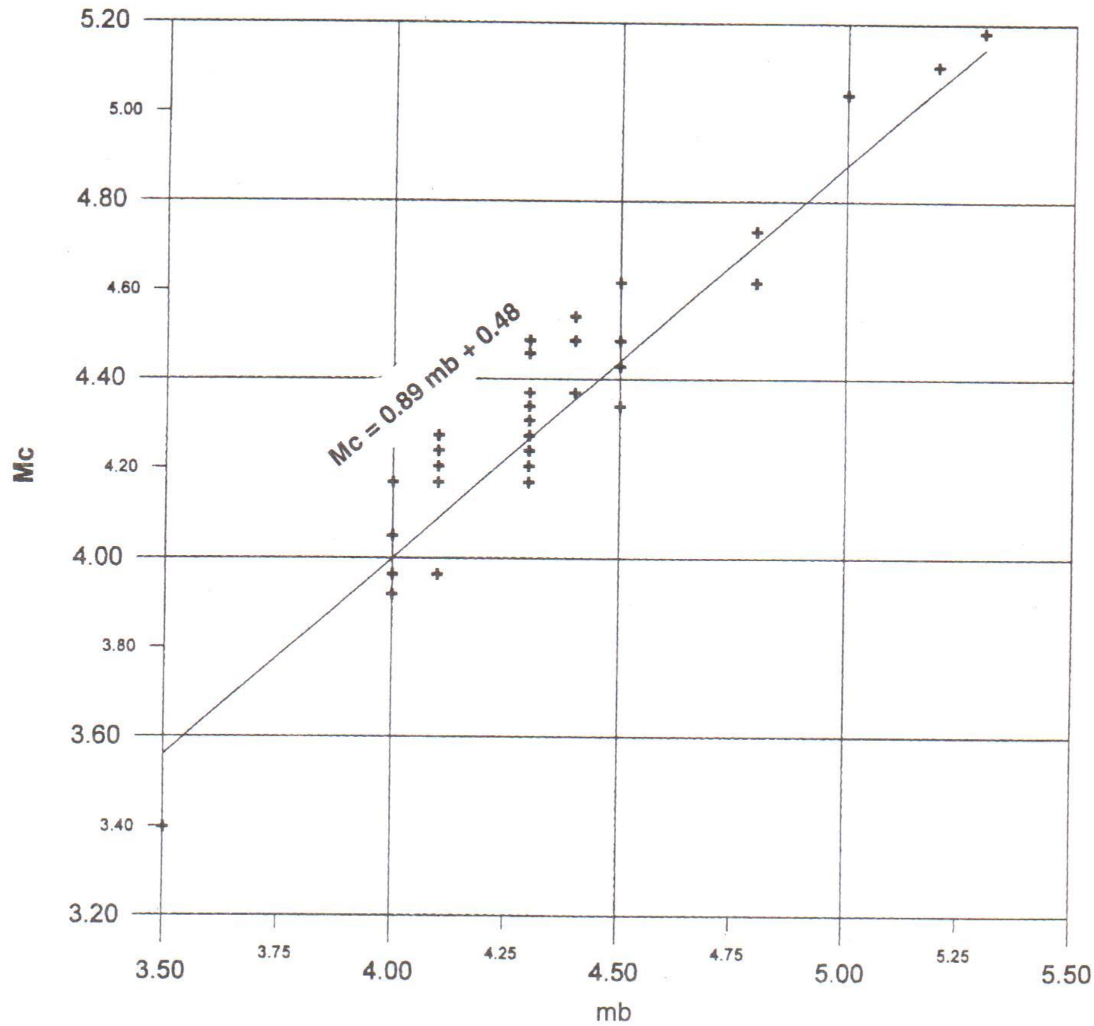

Fig. 6. Plottings of corresponding calculated coda magnitude (Mc) and observed body- wave magnitude (mb) values used in determining the empirical relation. Vertical axis is Mc and horizontal axis is mb.

Conclusions

The application of multiple regression techniques to magnitude calibration from amplitude and duration data from the seismic stations in the NW Saudi Arabia sub-network of SSC have yielded two magnitude formulas corresponding to two magnitude scales for use in estimating magnitudes of earthquake events in the Mediterranean region particularly in the Aqabah area. These were:

$ML = \text{Log}(A/T) + 3.4\,\text{Log}\,D + 2.55$ for amplitude and

$Mc = 2.55\,\text{Log}\,(t) - 2.15$ for coda duration.

The two magnitude scales are complimentary to each other. The coda magnitude scale is preferably useful for epicentral distances of less than 500 km due to negligible contribution of the distance correction factor and the possibility of amplitude saturation for analog recordings, while the adapted local magnitude scale can be reliably used for distances greater than 500 km due to back-scattering of the coda waves which are considered as surface waves and could possibly contribute to misinterpretations. Where the applicability of the coda magnitude is limited such as in the case of successive events, the adapted local magnitude can be used within some limitations. Hence, this supplementary function in each empirically determined magnitude scales could possibly contribute to better earthquake monitoring in the Mediterranean and Arab regions. However, further test and additional data could probably improve the findings for best results.

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معايرة القدر الزلزالي لشبكة الزلازل الفرعية في شمال غرب المملكة العربية السعودية

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ملخص البحث. تم تطوير صيغتين رياضيتين لحساب القدر الزلزالي للاستفادة منهما في تحديد المعاملات الزلزالية لشبكة الزلازل الفرعية في شمال غرب المملكة العربية السعودية هما :

$$ML = Log (A/T) + 3.4 Log D + 2.55$$
$$Mc = 2.55 Log (t) - 2.15$$

تم تحديد الصيغتين تقليديًا بواسطة معايرة القدر الزلزلي لسعة الموجه (المعادلة الأولى) وعن طريق معرفة الفترة الكلية (المعادلة الثانية) من ثمانية محطات زلزالية للشبكة الفرعية .

دلّت العلاقة ما بين القدر الزلزالي Mc، الفترة والمسافة أن معامل التصحيح يمكن إهماله للزلازل التي تبعد مسافة أقل من ١٠٠٠كم عن موقع الشبكة الفرعية . وهذا يؤدي بدوره إلى الاعتماد على مقياس القدر الزلزلي المحلي ML لإعطاء أفضل تقدير لقيم القدر الزلزالي . بينت هذه النتائج أن مقياسي الزلازل ML و Mc مكملين لبعضهما ويمكن استخدامهما لتغطية الأحداث الزلزالية في منطقة شرق البحر الأبيض المتوسط .

يستدل من مقياسي القدر الزلزالي على أن هنا تطابقا جيدا بخطأ قياسي قدره 0.16 للقدر الزلزالي المحلي ML و 0.12 للقدر الزلزالي Mc. كما أمكن، أيضًا، تحديد علاقات جيدة بين القيم المحسوبة من هذين المقياسين ومن قيم القدر الزلزالي للموجات الباطنية mb .

$$ML = 0.91\ mb + 0.39$$
$$Mc = 0.89\ mb + 0.48$$

ويمكن الاستفادة من تلك العلاقة للتأكد من حساب المعاملات الزلزالية من معرفة العلاقة الأخرى .