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# Calibration of the duration magnitude for the North-Eastern Italy Seismic Network (OX) on the basis of the revised local magnitudes of the Trieste station

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**ABSTRACT** The duration magnitudes in the North-Eastern Italy Seismic Network (OX) catalogue have been thoroughly revised. Historically, but also today for homogeneous continuity with the past, this catalogue, released yearly by the National Institute for Oceanography and Experimental Geophysics, provides local magnitudes in terms of duration magnitude ($M_D$). Unfortunately, the earthquake total durations were calibrated on a local Richter magnitude ($M_L$) data set characterized by a demonstrated small bias. In this work, based on a revised and corrected $M_L$ catalogue of the Trieste seismological station, computed in accordance with the original Wood Anderson requirements and validated in turn with the available moment magnitude estimates, new linear empirical regressions between $M_L$ and earthquake total duration have been performed, aimed at producing a homogeneous catalogue of locations and $M_D$ for the eastern Southern Alps.

**Key words:** local magnitude, duration magnitude, seismic network, NE Italy.

## 1. Introduction

Since the seminal paper by Richter (1935), the earthquake size has been described by magnitude. The original Richter (1935) magnitude ($M_L$) was defined for local earthquakes (distances less than 600 km) on the basis of the recordings of the Wood – Anderson (WA) torsion seismometer, whereas in the following years other types of magnitude were calibrated for local events as well as for teleseisms. Among those for local quakes, it is worth citing the duration magnitude ($M_D$), first introduced by Bisztricsany (1958), who used the surface wave duration, later considered by Soloviev (1965), who used the total signal duration to study the seismicity of the Sakhalin island, Tsumura (1967), who calibrated it for a local network in Japan, and Lee *et al.* (1972), who did the same for the network of central California.

Since the 1970s, only $M_D$ has been routinely computed for the regional seismic monitoring in Italy, as the few WA seismometers operating in this country, as well as abroad, were discarted in the course of the years and $M_D$ is still the standard magnitude for daily processing (Castello *et al.*, 2007).

The aim of this work is a new calibration of the formulae for the $M_D$ computation of the earthquakes recorded by the regional seismic network operating in north-eastern Italy.

## 2. Why a revision of the $M_D$ procedure for OX?

After the devastating earthquake of 1976 in Friuli (Finetti *et al.*, 1979; Carulli and Slejko, 2005; Slejko, 2018), the National Institute of Oceanography and Experimental Geophysics (OGS) deployed seismic stations in the epicentral area and later over the whole of north-eastern Italy. Since 1977, it has managed regional seismic monitoring and released yearly the catalogue of the earthquakes recorded by the North-East Italy Seismic Network (OX) where the magnitudes are provided in terms of $M_D$. The data elaboration is performed according to the HYPO71 (Lee and Lahr, 1975) standards and the catalogue is released only in electronic format at: www.crs.inogs.it/bollettino/RSFVG. A general description of the OX is available in Priolo *et al.* (2005). Some practical advantages have supported, and still do, the use of $M_D$ in the routine earthquake evaluations and localizations every day: simplicity and rapidity of computation, general independence from distance and azimuth of the event, low sensibility of the WA instrument to low magnitude events. Moreover, in the past there were problems related to signal saturation or underexposure on photographic records and, finally, $M_D$ had the advantage of avoiding the time needed for the laborious development of photographic paper to compute amplitude magnitudes. Nowadays, the Trieste WA is still operating but the recording system has switched from photographic to digital [using an optical laser converter, see Sandron *et al.* (2015)].

The Trieste (TRI) seismological station, belonging to the World Wide Standardized Seismographic Network (WWSSN), and the L'Aquila one in central Italy, were the only stations equipped with a pair of WA torsion seismographs in Italy. The TRI WA instruments (Lehner-Griffith TS-220) were installed in September 1971 for $M_L$ computation of the local earthquakes and continued recording till 1992 (even if the last value of $M_L$ reported in the TRI station bulletin dates 13 September 1989). Finetti and Morelli (1972) showed that no station correction was needed for the $M_L$ calibration considering the original Richter (1935) coefficients.

The first $M_D$ calibration for the Friuli area was proposed by Suhadolc (1978) using the WA data of the TRI station (28 earthquakes, 160 signal durations). A revision of the $M_D$ calibration for the TRI station was performed by Rebez *et al.* (1984) on the basis of a greater number of earthquakes (236 earthquakes). Rebez and Renner (1991) performed the second $M_D$ calibration for 21 stations of the OGS network (640 earthquakes, 4726 signal durations), considering again the TRI WA $M_L$. Even today, for homogeneous continuity with the past, the Rebez and Renner (1991) coefficients are still used in the normal daily routine of earthquake localization and (above defined magnitude thresholds) to notify the civil protection operators, the authorities involved in the emergency, and the media.

Unfortunately, the TRI $M_L$ was computed by combining the two horizontal components as a vector sum. According to the Richter (1958) definition, when using recordings of both horizontal components, it is preferable to compute the magnitude independently from each component and then to average the two estimates. As a consequence, the OX catalogue contains a recognised bias of +0.2 magnitude units (Gasperini, 2002). Sandron *et al.* (2015) reviewed and corrected the $M_L$ estimates for the period 1977 to 1988 and, taking the advantage of the renovation and new operation of the original WA since 2002, compiled a new catalogue of 1522 events with magnitude $0.2< M_L< 6.5$ for the time window 1977–2013.

It, then, seemed necessary to provide a new $M_D$ calibration for the stations of the OX network, on the basis of this new and updated $M_L$ data set, aimed at producing, for the first years of operation of the network, a catalogue with homogeneous magnitudes in agreement with those computed in the recent years. Not all stations considered by Rebez and Renner (1991) are taken into account in this study because the decision was made to relate the new regressions only to original $M_L$ data, appropriately corrected according to the revision of Sandron *et al.* (2015). Conversely, Rebez and Renner (1991) also used TRI $M_D$ estimates as $M_L$ data.

## 3. Available data

Dealing with the magnitude of local earthquakes, only original WA magnitude values have been considered in this study as independent variables to ensure the homogeneity of the data set. As a consequence, it has not been possible to calibrate $M_D$ for low magnitude events, where the WA records are usually not readable (Lee *et al.*, 1972). In agreement with the subdivision followed by Sandron *et al.* (2015) for the $M_L$ catalogue (essentially based upon the operation periods of the TRI WA instrument), we can identify two different periods (as detailed below) in which to subdivide our $M_L$ data set.

### *3.1. First period (1977 – 1992)*

The TRI station was the closest seismological station to the epicentre of the 1976 Friuli earthquake (about 70 km apart) and recorded the entire seismic sequence (Colautti *et al.*, 1976). During the seismic sequence, a temporary network was deployed in the epicentral area. On 6 May 1977, OGS activated the first 3 short-period stations (BAD, BUA, COLI, see details in Table 1 and Fig. 1) in the epicentral area, followed by a fourth (BOO) on 9 May a further two (MPRI and UDI) in June and RCL in August. Successively, a further eight stations until 1985 (Renner, 1995) improved the regional coverage of the network (RBL, CAE, DRE, ZOU, ERT, POBI, FOA and TAL).

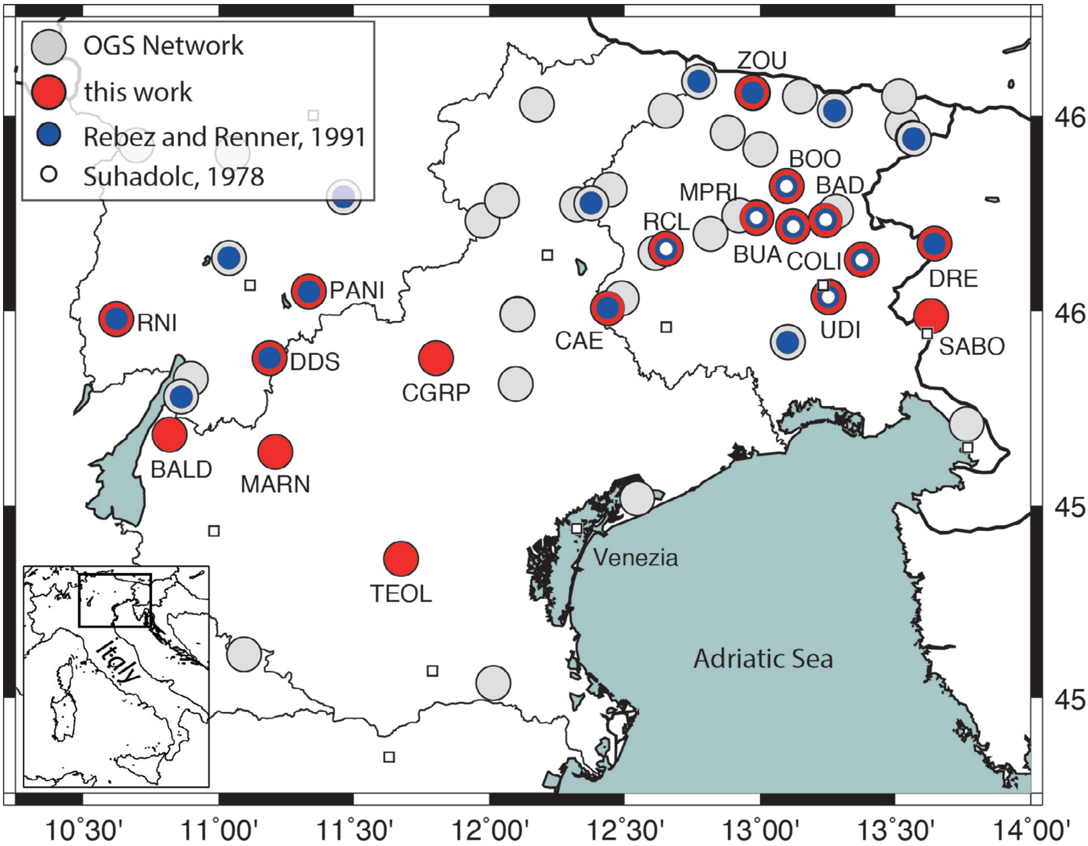

Fig. 1 – Stations of the OX seismic network in north-eastern Italy (grey circles). Coloured circles indicate the stations calibrated respectively by: white = Suhadolc (1978), blue = Rebez and Renner (1991), red = this study.

Table 1 - List of the seismic stations for which the linear fit between $M_L$ and earthquake total duration has been performed. For each is reported: the name (STA); the station code (ID); the geographical coordinates (Lat. N° and Lon. E°); the year of installation (Y); the number of data couples used (N); the slope of the line ($a_2$), the intercept of the line ($a_1$), the variation coefficient (R), and the range of validity (ΔM).

| STA | ID | Lat. N° | Lon. E° | Y | N | $a_1$ | $a_2$ | $R$ | $\Delta M$ |
|---|---|---|---|---|---|---|---|---|---|
| Bernadia | BAD | 46°14'03" | 13°14'36" | 1977 | 241 | -3.18 | 3.00 | 0.98 | 1.8-5.0 |
| Buia | BUA | 46°13'00" | 13°07'25" | 1977 | 220 | -2.79 | 2.83 | 0.98 | 1.8-5.0 |
| Colloredo | COLI | 46°07'56" | 13°22'36" | 1977 | 217 | -2.28 | 2.58 | 0.97 | 1.8-5.0 |
| M.te Prat | MPRI | 46°14'26" | 12°59'14" | 1978 | 198 | -2.76 | 2.82 | 0.99 | 1.8-5.0 |
| Bordano | BOO | 46°19'11" | 13°05'55" | 1978 | 204 | -2.95 | 2.93 | 0.98 | 1.8-5.0 |
| Valcellina | RCL | 46°09'36" | 12°39'12" | 1978* | 166 | -2.57 | 2.74 | 0.99 | 1.8-5.0 |
| Udine | UDI | 46°03'54" | 13°14'12" | 1978† | 140 | -2.70 | 2.81 | 0.98 | 1.8-5.0 |
| Caneva | CAE | 46°00'31" | 12°26'17" | 1983 | 65 | -3.81 | 3.33 | 0.99 | 1.8-3.5 |
| Drenchia | DRE | 46°10'24" | 13°38'42" | 1983 | 57 | -3.12 | 2.92 | 0.95 | 1.8-3.2 |
| Zoufplan | ZOU | 46°33'27" | 12°58'26" | 1983 | 70 | -3.79 | 3.29 | 0.99 | 1.8-3.2 |
| Roncone | RNI | 45°58'48" | 10°37'22" | 1981‡ | 43 | -3.91 | 3.36 | 0.99 | 2.1-3.5 |
| Panarotta | PANI | 46°03'00" | 11°20'02" | 1981 | 56 | -3.23 | 3.04 | 0.99 | 1.8-3.8 |
| Dosso | DDS | 45°52'48" | 11°11'18" | 1981 | 68 | -3.57 | 3.12 | 0.99 | 1.8-3.8 |
| C. Grappa | CGRP | 45°52'50" | 11°48'17" | 2001 | 93 | -2.16 | 2.39 | 0.98 | 2.1-4.1 |
| Teolo | TEO | 45°21'42" | 11°40'26" | 2002 | 73 | -1.94 | 2.31 | 0.94 | 2.4-3.8 |
| Marana | MARN | 45°38'16" | 11°12'36" | 2009 | 93 | -2.83 | 2.77 | 0.99 | 2.1-3.8 |
| Baldo | BALD | 45°40'59" | 10°49'05" | 2008 | 66 | -4.34 | 3.49 | 0.99 | 2.4-3.8 |
| Sabotino | SABO | 45°58'48" | 13°36'00" | 2008 | 66 | -1.78 | 2.24 | 0.99 | 1.8-3.1 |
| ALL | | | | 1977 | 2136 | -3.10 | 2.96 | 0.99 | 1.8-5.0 |

* closed 10 November 1995

† closed 5 May 1990

‡ closed January 2013

Apart from the changed number of stations making up the network and the instrument characteristics (all identical at the beginning), this data set can be considered homogeneous both from the acquisition and data analysis points of view. In fact, it was a continuous recording system of analogue data, where the event detection was made by visual inspections of the traces on an oscilloscope and the seismic phases were manually read from paper plots. Three hundred and seventy localized earthquakes have the TRI $M_L$ estimate, in the range 1.0 to 6.5, in this first operational period; only 245 of them also have the duration from at least one network station. Since the OGS network was a local network surveying the Friuli area, at that time, events outside that area of interest, even of large magnitude (recorded and documented in the bulletins of the TRI station), were not of concern. As a consequence, this set of locations is full of small and barely perceived earthquakes ($1<M_L<4$) and lacks earthquakes with an $M_L$ greater than 4. For this reason, a subset of 30 events external to Friuli in the $M_L$ range 4.5 to 6.5 have been selected, the original records have been retrieved from the OGS archive and their total durations have been read. Unfortunately, only the paper printouts are still available while the original data signals, recorded on analogue tapes, are no longer readable.

### *3.2. Second period (2002-2005 and 2010-2013)*

The upgraded TRI WA seismometer (the recording system changed from analogic to digital) was again operating in 2002. A gap from 26 May 2005 to 5 March 2010 was owing to the relocation of the instruments from their historical site (solid rock basement anchored on Karst limestone) to a temporary position because of the restoration of the hosting building. Over the years, OGS has become the reference institute for the seismic monitoring of the whole of north-eastern Italy and at present the OX network (doi:10.7914/SN/OX) monitors whole north-eastern Italy, with a total of 40 (seismometric and/or accelerometric) stations, of which 16 are equipped with short-period seismometers, 22 with broad-band seismometers, and 21 with accelerometers. The area that OGS covers, inside which earthquakes are located with adequate precision, ranges from latitudes 44.50° N to 47.00° N (from the Po River, to the south, to the border with Austria, to the north) and longitudes from 10.00° E to 14.50° E (from Lake Garda, to the west, to the border with Slovenia, to the east) .

For this second operational time interval, data of 1152 localized earthquakes with a TRI $M_L$ in the range 0.5 to 5.8 are available; only 532 of them also have the duration from at least one network station. Since there are only 336 localized earthquakes till 2005, the second homogeneous period can in practice be considered to start from 2010, with a fully digital data system along with an automatic acquisition, elaboration and data storage. BALD, MARN, SABO, TEOL (see Fig. 1) are the stations belonging to this recent digital epoch for which data for this research (location, TRI $M_L$, and the duration estimate of at least one station of the network) are available.

## 4. Data elaboration

The core of this work consisted of collecting station durations and TRI $M_L$ estimates for later generating scaling laws between these two quantities. The intersection between the TRI $M_L$ and the station total duration data sets for each earthquake was performed in an open source database management environment (Apache OpenOffice). Briefly, the yearly OX bulletin files reporting station phases and duration readings (also available at www.crs.inogs.it/bollettino/RSFVG/) for each earthquake were reorganized to create separate station duration tables. Then we crossed these tables with the TRI $M_L$ catalogue, obtaining for each station an individual table with earthquake origin time and both TRI $M_L$ and total duration.

The total number of localized earthquakes with the TRI $M_L$ and at least one duration reading is 777, corresponding to 2136 durations, and these data are used for the following analyses. The magnitude distribution of the events, grouped on 0.3 magnitude bins is shown in Fig. 2a. As stated before, in the first period there is a lack of earthquakes with $M_L$>3 and the most representative value is $M_L$=2.8 (red bars in Fig. 2a). The second part of the catalogue is well represented till $M_L$=2.5 (orange bars in Fig. 2a). Considering the full catalogue (blue bars in Fig. 2a) the most abundant classes are in the range 2.4<$M_L$<3.2.

Unfortunately, the total duration is not always available for all the stations simultaneously: in general, at each station the number of total duration readings is less than 50% of the number of earthquakes recorded (Fig. 2b). For example, stations RCL and UDI, operating only in the first period, have a percentage of readings of 45% and 38%, respectively. As regards the second period, except MARN, installed in 2009 with a ratio equal to 50%, the other stations have a reduced number of duration readings (Fig. 3). As mentioned before, today the OGS seismologists continue to read duration only for continuity with the past (hence rather reduced in number), because

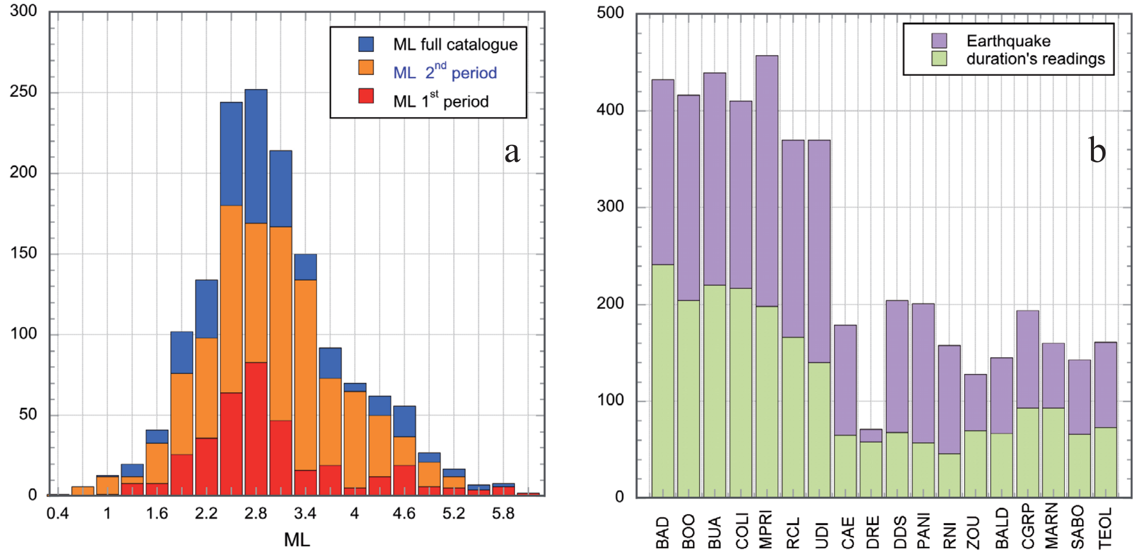

Fig. 2 – Data description: a) earthquake magnitude distribution of the events, grouped in 0.3 magnitude bins, of the whole catalogue (blue bars), the first period (red bars) and the second period (orange bars); b) data available for each station (see Table 1) in terms of numbers of earthquakes recorded (magenta bars) and total duration readings (green bars).

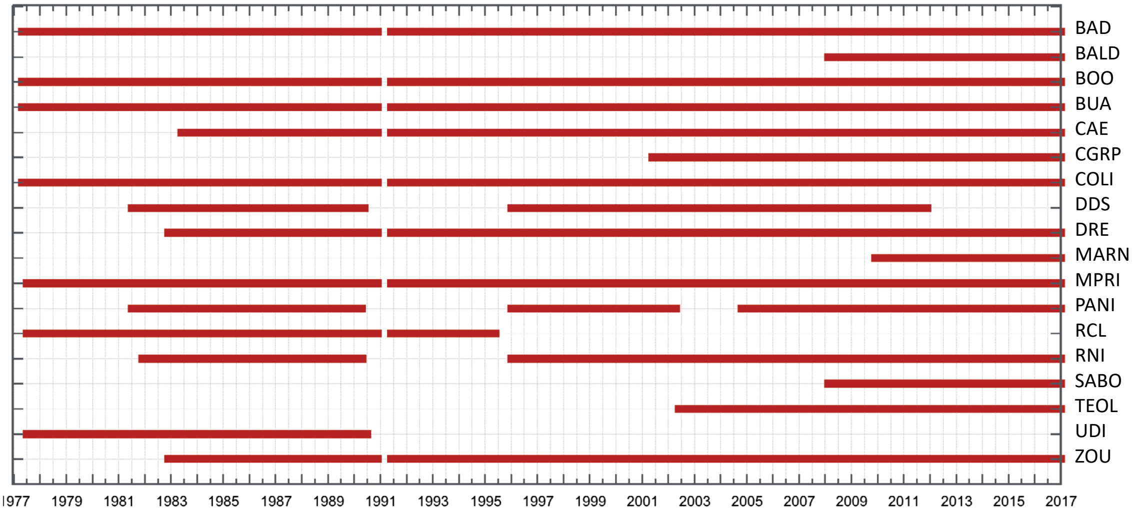

Fig. 3 – Operation periods of the stations of the OX seismic network considered in this study.

now the almost fully automated system, calculates $M_L$ (on broadband WA filtered waveforms) as well as the moment magnitude ($M_W$) whenever possible to compute it (usually for magnitude $\geq 3.5$). Moreover, the TRI WA seismograph lost its crucial role, as it was no longer a single stand-alone instrument but ran in tandem with a modern broadband instrument. In addition, since the beginning of the 21st century, there is a reduced seismicity recorded in the OGS monitoring area. The seismic sequence recorded after the 20 May 2012 Emilia earthquake ($M_L$=5.7) is very close to the border of the OGS area of competence and quite far from Trieste (about 400 km): several data of the study here come, then, from that sequence. The largest magnitude recorded before this sequence is $M_L$= 4.5 (29 October 2011) and $M_L$= 5.0 in (24 November 2004) after the WA retrofitting. For this reason, the range of applicability of the empirical regression for the stations with more recent data is limited.

Table 1 lists the 18 seismic stations considered in this work; for each of them is reported: the name (STA); the station code (ID); the geographical coordinates (Lat. N° and Lon. E°); the year of installation (Y). The parameter N stands for the number of data couples available in defining the empirical relationships between $M_L$ and earthquake total duration.

The first elaboration has considered all the data points and a linear least squares regression has been performed (see Fig. 4) according to the formula:

$$M_L = a_1 + a_2 \mathrm{Log}\,(t) \qquad (1)$$

where $M_L$ is the TRI $M_L$, $t$ is the total duration in seconds [from the onset of the first P-arrival to the point where the trace amplitude becomes lost in the noise (see Real and Teng, 1973)] at the selected station, and $a_i$ are the station coefficients. Rebez and Renner (1991) also introduced in their work a coefficient for the station-to-event epicentral distance correction, but underlining at the same time that nearly all of them are very small (in the order of $10^{-3}$) and that their contribution to the attenuation term can be neglected (see also Lee *et al.*, 1972). In practical use, in the daily routine, the OGS staff have never used this factor. Instrument sensitivity has been ignored as well because almost all of the instruments are identical and the instrument amplification is adjusted according to the background noise level, thereby compensating the effects of local site conditions (see Lee *et al.*, 1972).

The obtained results have not been considered satisfactory as the large number of low-magnitude events conditions the regression heavily; in fact, the variation coefficient for the different stations ranges between 0.68 and 0.89. It has been decided, then, to follow an alternative approach, consisting of: 1) first to group the $M_L$ values in 0.3 non-overlapping magnitude bins, 2) then, to compute the mean value of earthquake total durations inside each single bin and to associate it to the central value of the bin itself; and 3) finally, to interpolate the obtained couples of data with the simple linear regression of Eq. 1.

The new correlations between $M_L$ and Log($t$) for each station listed in Table 1 are plotted in Fig. 4. It can be seen that the computed coefficients are significantly different from each other and hence justify the initial choice of using individual regressions for the different station instead of introducing station corrections. The computed $R$ index is almost constant, between 0.98 and 0.99, with only two stations with a worse value. These estimates indicate, then, a good fit of the data.

## 5. Discussion and remarks

### *5.1. Limits of the data set*

The updated version of the $M_D$ calibration for the OGS OX network, thanks to the new and revised TRI estimates, has produced individual formulae for $M_D$ computation (coefficients in Table 1) that can be adopted for a complete and homogeneous revision in the magnitude content of the whole OGS catalogue.

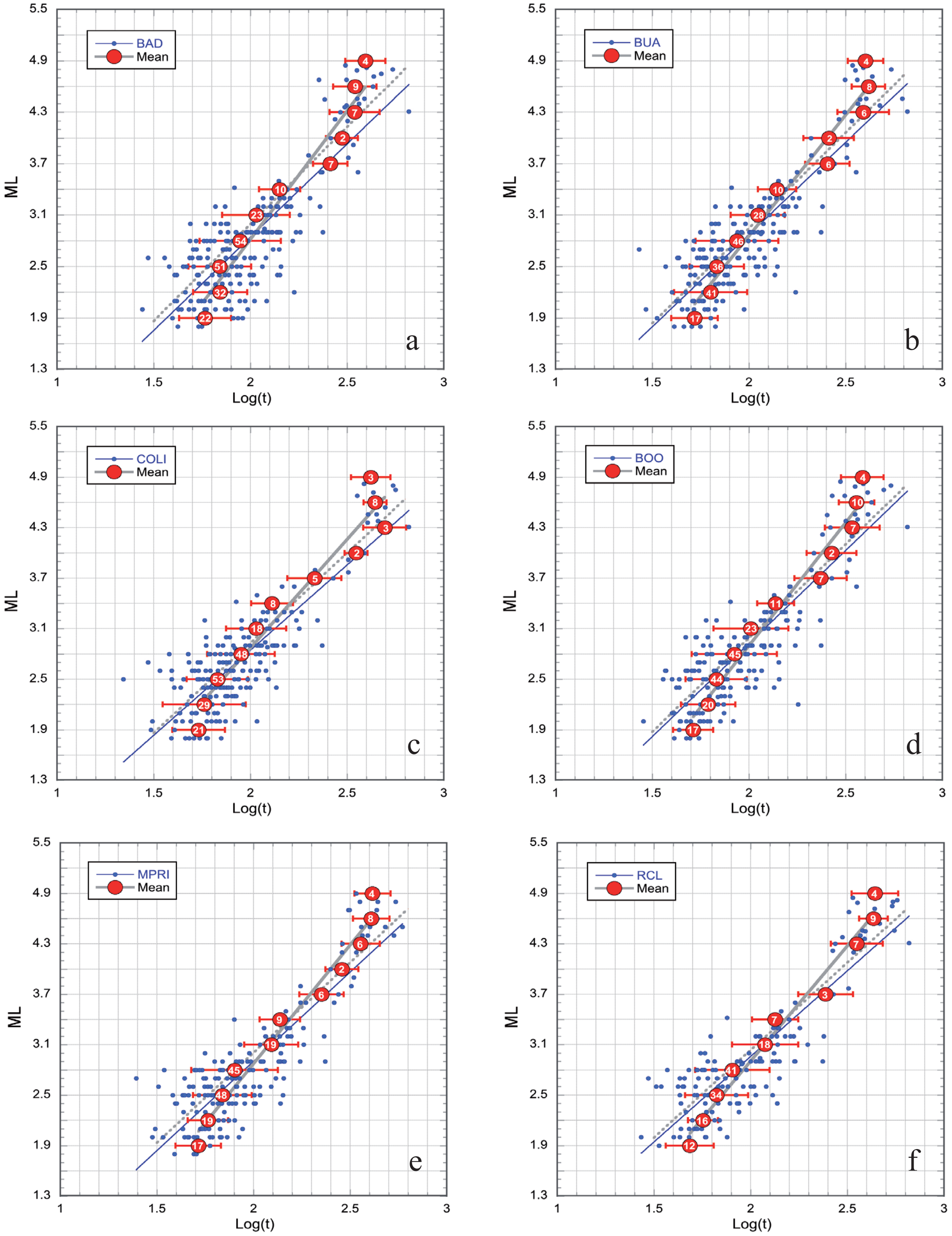

Fig. 4 - Correlation between $M_L$ and Log($t$) for the stations listed in Table 1. Small blue circles are the available data (column N in Table 1) and the thin blue line is the linear fit. The solid red circle stands for the mean value of the logarithm of total durations falling inside the corresponding 0.3 $M_L$ bin. The number of entries in the mean computation is reported inside the red circle and the horizontal bar indicates the standard deviation. The solid grey line is the linear fit following Eqn. 1; the dashed black line is the linear fit according to Suhadolc (1978); the dotted grey line is the linear fit according to Rebez and Renner (1991).

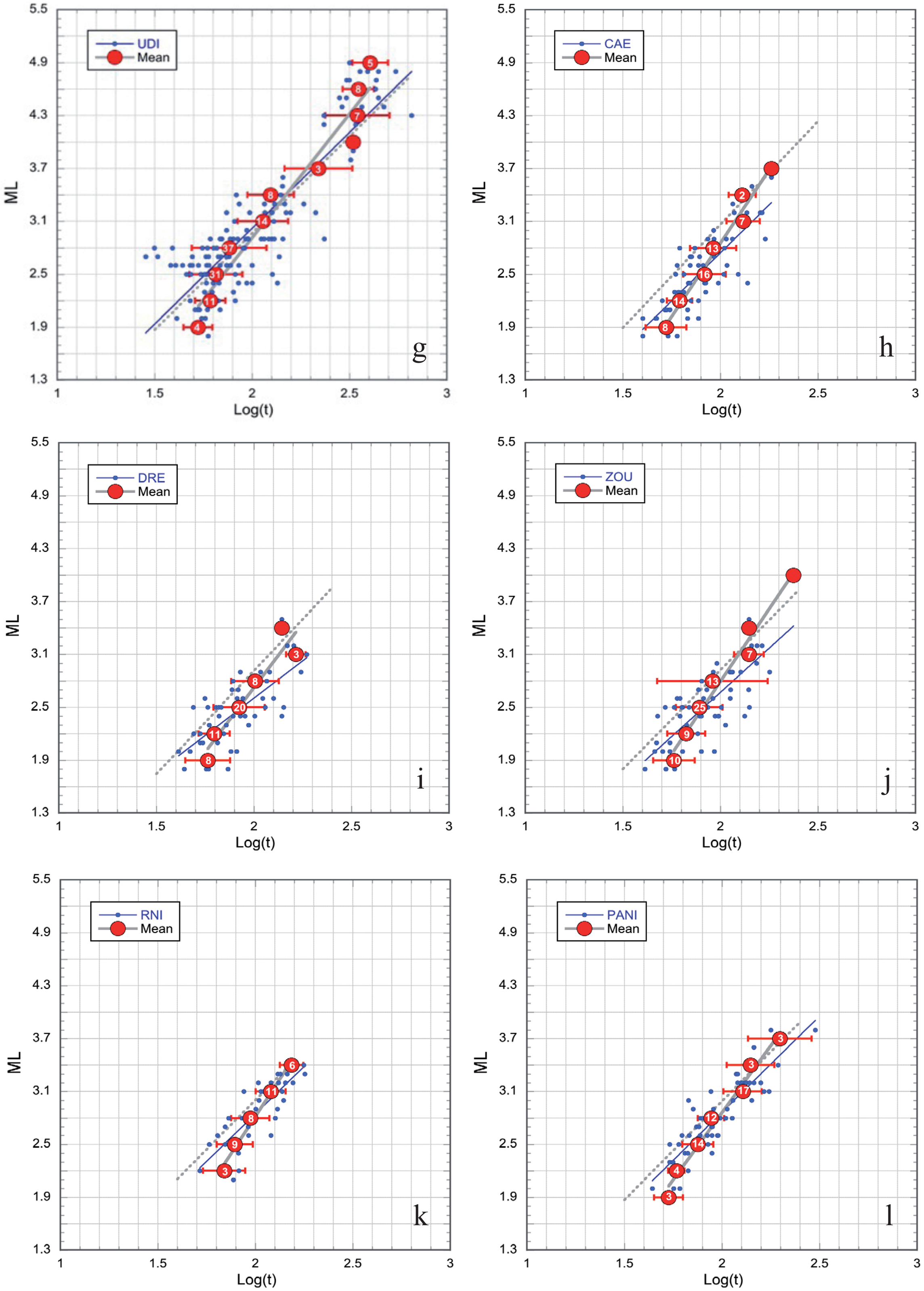

Fig. 4 - continued.

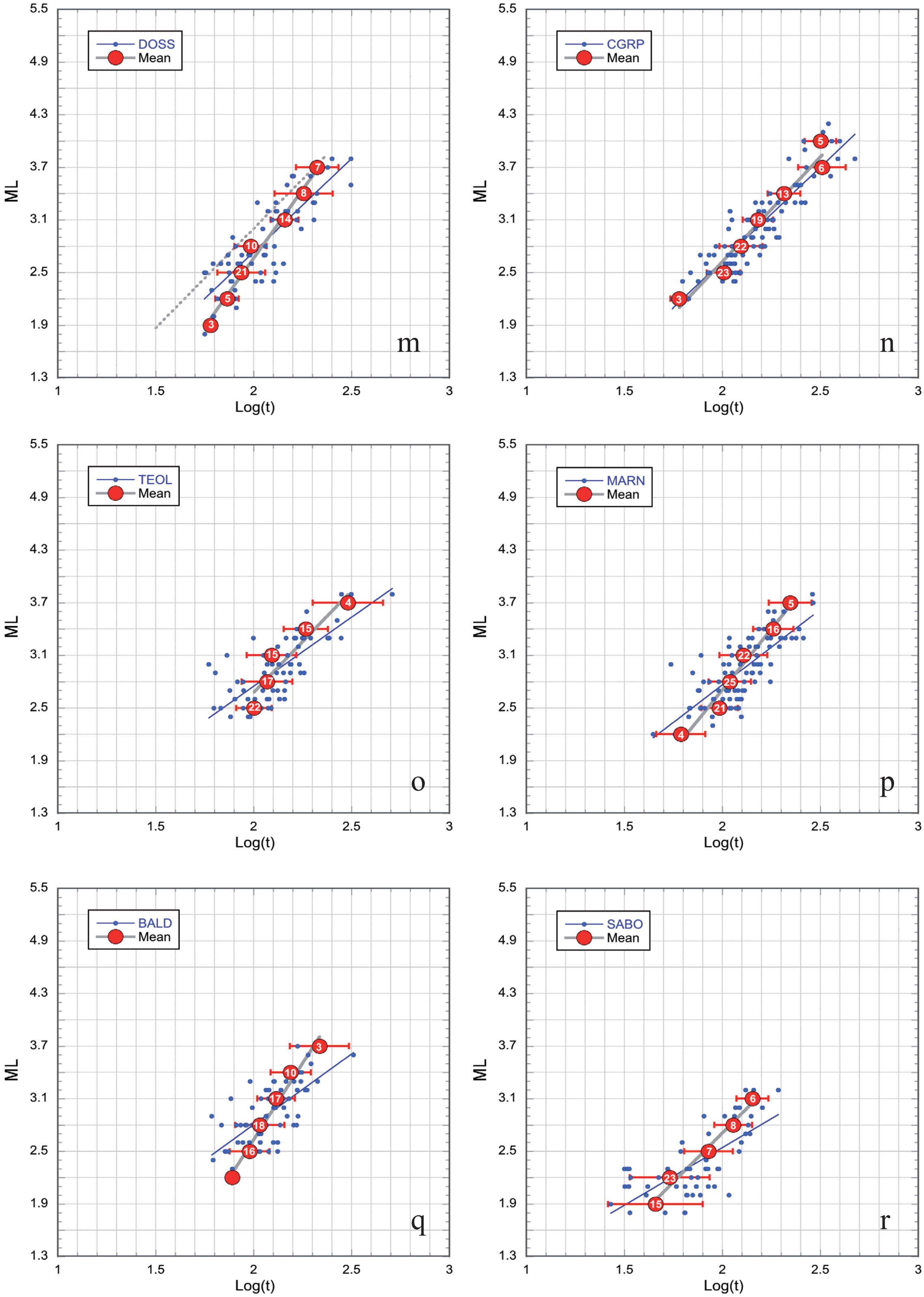

Fig. 4 - continued.

As cited before, only the paper printouts are still available for the earthquakes recorded by the OX network before 1992 and, after reading the additional 30 events outside Friuli, we realized that the signal tracks on paper are often prematurely cut and that our readings, also those that we were reasonably confident about, are shorter than expected, e.g. according to the Rebez and Renner (1991) relationships. We, thus, decided to adopt $M_L$= 5 and $M_L$= 1.8, respectively, as upper and lower limits for our regression analysis. This magnitude range (see Table 1) is even shorter for some stations, depending also on the available data which, particularly for recent years, are very limited.

### *5.2. Linear fit method*

We are aware that adopting to compute the correlation between $M_L$ and Log($t$) is subjective and thus questionable, above all regarding the limited number of data available. On the other hand, the choice to compute the regressions using a simple linear least squares fit on the mean values of duration data within the magnitude bins (red points in Fig. 4) is mainly due to the fact that a standard regression using all the magnitude values [as in Rebez and Renner (1991)], reported as dashed grey line in Fig. 4, is dominated by the high number of samples of low to intermediate $M_L$ (between 2.0 and 3.5). In fact, the linear fit on the same duration database, but using the new $M_L$ values, is simply parallel to that of Rebez and Renner (1991) with an almost constant offset of 0.2 magnitude units, which is the recognized bias of the old OGS catalogue (Sandron *et al.*, 2015).

This kind of approach, based on mean values of the dependent variable, was previously adopted by Cavallini and Rebez (1996) in the definition of a scaling law between macroseismic intensity and surface wave magnitude and was applied for the construction of the Italian earthquake catalogue (Gruppo di Lavoro CPTI, 1999).

Similarly, Slejko *et al.* (2008) produced a linear regression between macroseismic intensities and peak ground acceleration on the data of the 1976 Friuli earthquake and the same method has also been adopted by Tselenis and Danciu (2008) and by Bilal and Askan (2014) to define felt intensity and ground motion relationships.

The method applied here is particularly suitable if the database is discontinuous and there are few values in certain classes of one of the two variables considered. This is certainly true for a macroseismic data set, which has plenty of low to medium intensity values and lacks data of the most powerful earthquake classes, but also in our case low magnitude events dominate and condition a simple linear regression.

Comparing these new equations with those provided by Rebez and Renner (1991), it can be seen from Fig. 4 that the magnitude variation is significant for $M_L$ values outside the range 3.0 to 3.5. As an example, considering a duration of about 80 s, recorded by the station BOO, a magnitude reduction of about 0.3 magnitude units is obtained. A similar variation, in this case with an increasing estimate, occurs also for the high magnitudes where a greater accuracy is required.

An additional check has been performed for the BAD station, chosen as an example because of its large amount of data (Table 1). The difference obtained using a different regression has been estimated considering the orthogonal fit (black line in Fig. 5) both adopting equal variances or imposing a variance ratio (in this case 2) to the $X$ and $Y$ quantities. The trend of the orthogonal regression is almost the same as that obtained by Eq. 1 for the $M_L$ range 1.8 to 5.0.

### *5.3. Full data correlation*

In the daily routine activity, the earthquake localizations performed by the automatic system is done using the HYPO71 (Lee and Lahr, 1975) standards. The specific station formulae adopted for the $M_D$ computation are those elaborated by Rebez and Renner (1991) who did not compute a general average formula suitable for all stations of the network, conversely to what Suhadolc (1978) did.

In the years following the Rebez and Renner (1991) study, new stations were deployed in Friuli and instead of calibrating the specific scaling laws for the new stations, a general scaling law was roughly calculated by averaging the coefficients of the existing formulae. In such a way, the contribution of the less sampled stations surely has an erroneous influence. A more robust result is acquired producing a linear fit on the whole data set: this is what has been done with the 2136 couples $M_L$-Log($t$) available in the present study. The obtained result is reported in Fig. 6 and the coefficients (to be applied in Eq. 1) are reported in Table 1. It is not surprising that the obtained coefficients mirror quite well those of the station with the largest number of observations (BAD, see Table 1).

### *5.4. Comparison with previous studies*

According to Suhadolc (1978), almost 50% of the data used are from the 16 September 1977 Friuli earthquake and the values of WA magnitudes are within a very limited range (2.7-3.7), though the validity of the regression formulae (blue dotted line in Fig. 7) is assumed extended to the range $1.5<M_L<4.0$.

A decade later, with more data available also from the expansion of the network, the data set used by Rebez and Renner (1991) suffered from the same limitation: a large number of small earthquakes ($1<M_L<4$) and the lack of duration readings for stronger ($M_L>4$) events.

A comparison among the present results and those from literature has been done considering the average formulae valid for all the stations involved. As concerns the different sets of stations investigated in this study, the average relations introduced hereafter have been computed

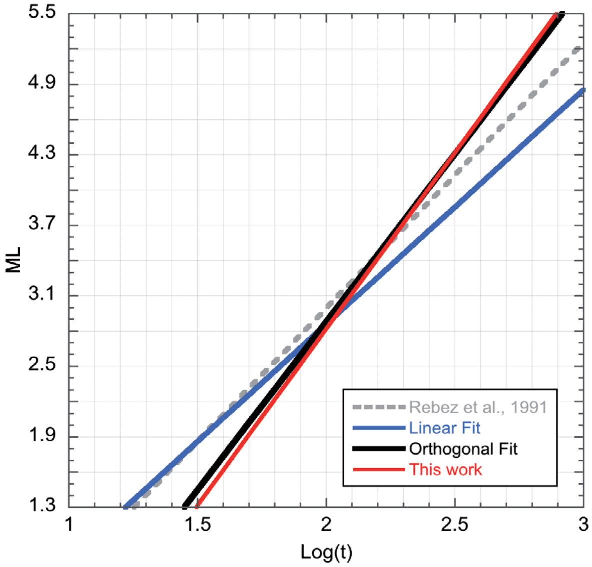

Fig. 5 - Correlation between $M_L$ and Log($t$) for BAD station. The grey dashed line shows the linear fit according to Rebez and Renner (1991); the blue line is the linear fit of all the data in the range $1.8<M_L<5.0$; the black line is the orthogonal fit with a variance ratio equal to 2 for data in the same range of magnitude and the red line is the linear fit following Eq. 1.

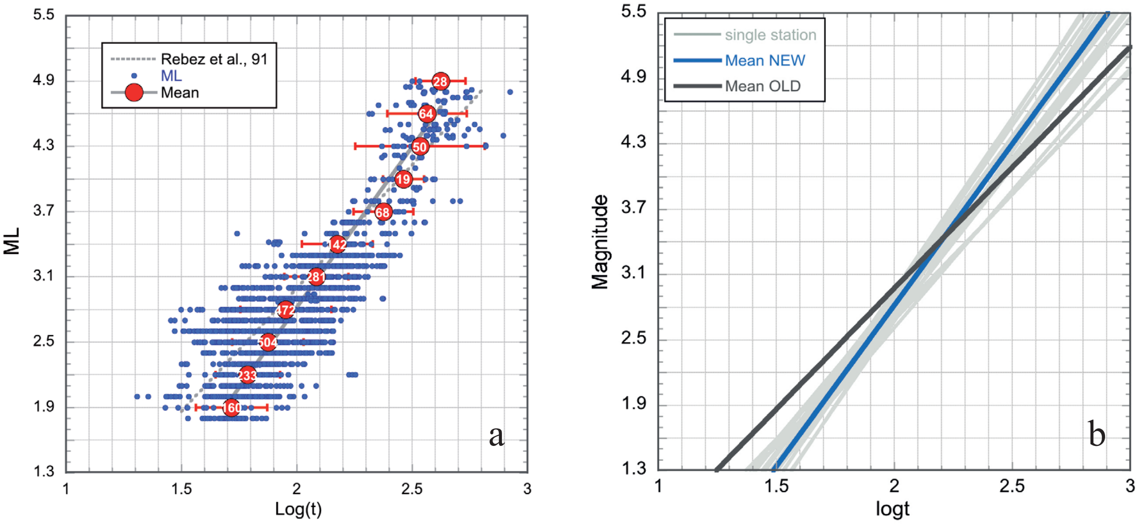

Fig. 6 - Global correlation between $M_L$ and Log($t$) for all stations listed in Table 1: a) the new fit based on mean duration values and Eq. 1; b) individual station fit line (grey solid lines), fit line for all data (blue solid line corresponding to that in panel a), fit line for all data according to Rebez and Renner (1991) (black solid line).

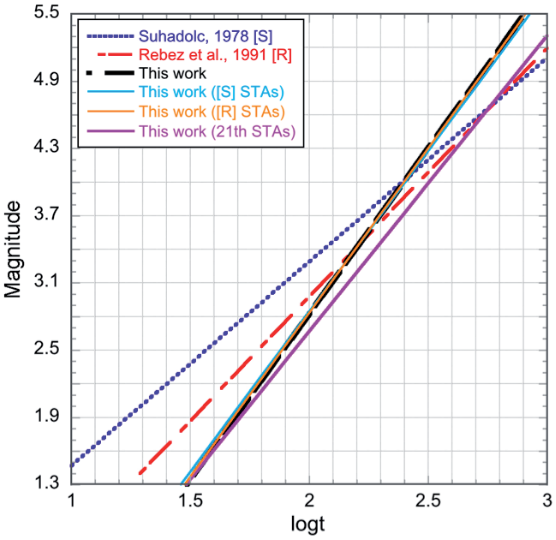

Fig. 7 – Mean linear fit according to: Suhadolc (1978) (blue dotted line); Rebez and Renner (1991) (red dashed line); Eq. 1 of this work (thick black dashed line); Eq. 1 of this work based on the first 7 stations [S] installed within 1978 and the same used by Suhadolc (1978) (thin light blue line); Eq. 1 of this work on common stations [R] with Rebez and Renner (1991) (thin orange line); Eq. 1 of this work by considering only the stations installed after 2001 (thin violet line), see Table 1 for details.

in a similar manner as previously described for the whole data set (line ALL in Table 1). In this work, the role of the re-read total durations of earthquakes in the range 4.5<$M_L$<6.5 is crucial.

These events mainly belong to the first period of activity of the network and for this reason there is no difference between the regression of our final whole data set (thick black dashed line in Fig. 7), the regression obtained considering only data of the first seven stations (BAD, BOO, BUA, COLI, MPRI, RCL, UDI) used also by Suhadolc (1978) (thin light blue line in Fig. 7), and the regression considering the stations of our data set already taken into account by Rebez and Renner (1991)(thin orange line). Conversely, a different trend (violet thin line in Fig. 7) is shown by the regression done using only recent data (CGRP, TEO, MARN, BALD, SABO), namely data from stations installed after 2001 that recorded only moderate seismicity (in general $M_L$<3.8): the difference, in this case, increases with increasing $M_L$ value.

Comparing the present results with those in the literature (Suhadolc, 1978; Rebez and Renner, 1991), it can be seen (Fig. 7) that the new relation underestimates the low events [$M_L$<4 for Suhadolc (1978) and $M_L$<3 for Rebez and Renner (1991)] and overestimates the larger ones. A more detailed analysis is visible in Fig. 4, where the regressions for the individual stations calculated by Suhadolc (1978) and Rebez and Renner (1991) are reported for comparison with the results here.

### *5.5. The impact of this study*

The impact of applying the new relationships between $M_L$ and Log($t$) to the data (durations) of the OX catalogue is quite relevant. Applying, as an example, the new station equations to the whole earthquake duration data set for the year 1985 (thus involving stations belonging to the first period) a general and expected $M_D$ underestimation is obtained with respect to the official estimates reported in the OX catalogue. The difference (Fig. 8a) between the results obtained by Rebez and Renner (1991) and the present equations is not constant, due to the intersection of the two regressions at about $M_L$=3.5 (+/- 0.5) and, consequently, the gap becomes greater and greater moving towards smaller ($M_L$<3) and larger ($M_L$>4) magnitudes. The grey circles in Fig. 8a represent the $M_D$ values (plotted as sequential events from the beginning of the year) obtained by applying the Rebez and Renner (1991) formula while the small solid blue circles show the $M_D$ values obtained applying the new formula. On the same plot, the same values with the same colours are superimposed in an $M_D$ descending order (based on Eq. 1). According to the new formula, almost 50% of the earthquakes would have an $M_L$ lower than 1.0 and 17% a negative value. The same conclusions are reached also considering the data for the year 2013 (Fig. 8b).

In light of the notable reduction in the $M_D$ estimations obtained with the new formulae, we were curious to check the validity of our results with the estimates of other seismological agencies. We then compared the new $M_D$ values with those published by the Slovenian ARSO agency (http://www.arso.gov.si) for a couple of years (namely 2014 and 2015). Thirty-six common events have been found (Table 2) and, as can be seen in Fig. 9a, the new $M_D$ estimates are greater than those of ARSO for $M_L$ greater than 1.5. Conversely, for $M_L$<1.5, OGS values are slightly lower than those of ARSO. As an additional piece of information, it is worth noting that all the $M_W$ estimates calculated by Moratto *et al.* (2017) for quakes with an $M_W$ greater than 1.5 are larger than the ARSO $M_L$ values, while the difference with the new $M_D$ proposed here is on average equal to -0.1 (Fig. 9b).

## 6. Conclusions

New regressions have been calculated for the $M_D$ computation of the earthquakes recorded by 18 stations of the OX network based on the recent revision of the WA $M_L$ values of the TRI station (Sandron *et al.*, 2015). A non-conventional approach, based on mean values of the dependent variable, has been applied for the regression analysis, because of the large quantity of data referring to small magnitudes, and the results obtained show notable differences from those of Rebez and Renner (1991). The quality of the regressions done are satisfactory, with an $R$-value generally between 0.98 and 0.99.

Table 2 – Magnitude estimates according to different sources (see the text for more details): $M_{lv}$ = ARSO, $M_D91$ = Rebez and Renner (1991), $M_D$, = this work, $M_W$ = Moratto *et al.* (2017).

| n | Y | M | D | HH | MM | SS | LAT | LON | $M_{lv}$ | $M_D91$ | $M_D$ | $M_W$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2015 | 1 | 12 | 0 | 11 | 14.3 | 45.53 | 14.29 | 1.5 | 1.7 | | |
| 2 | 2015 | 1 | 22 | 14 | 1 | 33.8 | 46.4 | 13.78 | 1.1 | 1.7 | 1.2 | |
| 3 | 2015 | 2 | 14 | 9 | 31 | 35.6 | 46.28 | 13.68 | 1.8 | 2.4 | 2.2 | 2.2 |
| 4 | 2015 | 3 | 22 | 15 | 46 | 49.5 | 45.76 | 14.04 | 2.1 | 2.7 | 2.4 | 2.4 |
| 5 | 2015 | 7 | 20 | 19 | 7 | 27.5 | 46.33 | 13.29 | 1.6 | 2.3 | 2.0 | 2.1 |
| 6 | 2015 | 7 | 24 | 6 | 35 | 43.4 | 46.3 | 13.6 | 1.5 | 1.8 | 1.2 | 1.9 |
| 7 | 2015 | 8 | 29 | 18 | 47 | 3.9 | 46.32 | 13.61 | 3.9 | 4.3 | 4.4 | 4.0 |
| 8 | 2015 | 8 | 29 | 19 | 29 | 1.7 | 46.32 | 13.61 | 1.6 | 2.2 | 2.0 | 1.9 |
| 9 | 2015 | 8 | 30 | 0 | 2 | 50.4 | 46.32 | 13.6 | 0.8 | 1.4 | 0.7 | 1.6 |
| 10 | 2015 | 9 | 18 | 7 | 52 | 20.1 | 46.46 | 13.44 | 1.7 | 2.1 | 1.5 | 2.1 |
| 11 | 2015 | 9 | 22 | 20 | 30 | 12.1 | 46.03 | 14.04 | 1.3 | 2.3 | 2.0 | 1.9 |
| 12 | 2015 | 9 | 23 | 1 | 53 | 9.8 | 46.32 | 13.6 | 2.1 | 2.8 | 2.7 | 2.4 |
| 13 | 2015 | 10 | 17 | 19 | 37 | 39.3 | 46.32 | 13.61 | 1.5 | 2.1 | 1.8 | 2.0 |
| 14 | 2015 | 10 | 31 | 18 | 26 | 30.9 | 45.85 | 13.55 | 1.4 | 2.2 | 1.9 | 1.9 |
| 15 | 2015 | 12 | 4 | 9 | 58 | 50.3 | 46.33 | 13.69 | 1.5 | 2.1 | 1.7 | 2.1 |
| 16 | 2015 | 12 | 15 | 5 | 6 | 18 | 46.3 | 13.67 | 2.2 | 3 | 2.9 | 2.5 |
| 17 | 2014 | 1 | 1 | 12 | 29 | 3.2 | 46.2 | 13.55 | 1.8 | 2.4 | 2.1 | 2.1 |
| 20 | 2014 | 6 | 24 | 22 | 43 | 25.1 | 46.25 | 13.76 | 2.6 | 2.8 | 2.7 | 2.9 |
| 21 | 2014 | 7 | 20 | 14 | 6 | 34.9 | 46.49 | 13.66 | 1.1 | 1.6 | | 1.6 |
| 22 | 2014 | 7 | 20 | 14 | 44 | 56.6 | 46.5 | 13.68 | 1.8 | 2.4 | 2.1 | 2.4 |
| 23 | 2014 | 7 | 27 | 9 | 33 | 20 | 45.58 | 14.3 | 1.7 | 2.2 | 1.9 | 1.9 |
| 24 | 2014 | 7 | 27 | 16 | 41 | 13.2 | 46.34 | 13.72 | 1.5 | 1.8 | 1.5 | 1.7 |
| 25 | 2014 | 8 | 21 | 20 | 28 | 37.1 | 46.1 | 13.52 | 2.1 | 2.6 | 2.3 | 2.3 |
| 26 | 2014 | 8 | 29 | 10 | 29 | 18.2 | 46.46 | 13.73 | 1.6 | 2 | 1.5 | 2.1 |
| 27 | 2014 | 9 | 12 | 15 | 50 | 52.6 | 46.47 | 13.41 | 1.8 | 2.3 | 2.1 | 2.4 |
| 28 | 2014 | 9 | 12 | 15 | 53 | 46.1 | 46.47 | 13.4 | 1.6 | 2.1 | 1.7 | 2.3 |
| 29 | 2014 | 10 | 1 | 0 | 41 | 34.5 | 46.52 | 13.68 | 1.2 | 1.9 | | 1.8 |
| 30 | 2014 | 10 | 12 | 5 | 11 | 38.5 | 46.31 | 13.27 | 1.5 | 2 | 1.8 | 2.0 |
| 31 | 2014 | 10 | 20 | 5 | 45 | 2.6 | 46.63 | 13.82 | 1.6 | 1.9 | 1.4 | 2.0 |
| 32 | 2014 | 11 | 22 | 3 | 22 | 34.9 | 46.33 | 13.66 | 1.8 | 2.3 | 2.0 | 2.2 |
| 33 | 2014 | 11 | 22 | 10 | 24 | 18.9 | 46.32 | 13.64 | 1.1 | 1.5 | 0.9 | 1.6 |
| 34 | 2014 | 11 | 24 | 14 | 28 | 46.8 | 46.32 | 13.65 | 1 | 1.4 | 0.8 | 1.6 |
| 35 | 2014 | 12 | 7 | 8 | 0 | 35.3 | 46.12 | 13.62 | 1.7 | 2.4 | 2.1 | 2.3 |
| 36 | 2014 | 12 | 7 | 9 | 48 | 53.7 | 46.11 | 13.62 | 1.6 | 2.1 | 1.6 | 2.0 |

The new formulae presented in this work can be used to replace those currently used (Rebez and Renner, 1991) in the $M_L$ range 2.0 to 5.0 in the daily routine activity of earthquake monitoring and localization entrusted to OGS for north-eastern Italy. The main target is, on the other hand, the application of these new scaling laws to the whole data set of earthquakes recorded since the first installation of the OGS seismic network. This would enable achieving a complete and homogeneous earthquake catalogue, also suitable for investigating the low-level seismicity of the eastern Southern Alps. As an example of the impact that the new relations can produce, Fig. 10 shows the Gutenberg - Richter relations calculated respectively with the existing formulae and those presented here. As all events recorded by the OX network since its deployment have been considered in this study, the changes made over time to the network geometry and number of stations cannot guarantee a kind of space completeness in the analyses performed. This means that the *b*-values calculated do not have a seismological meaning but simply illustrate the different

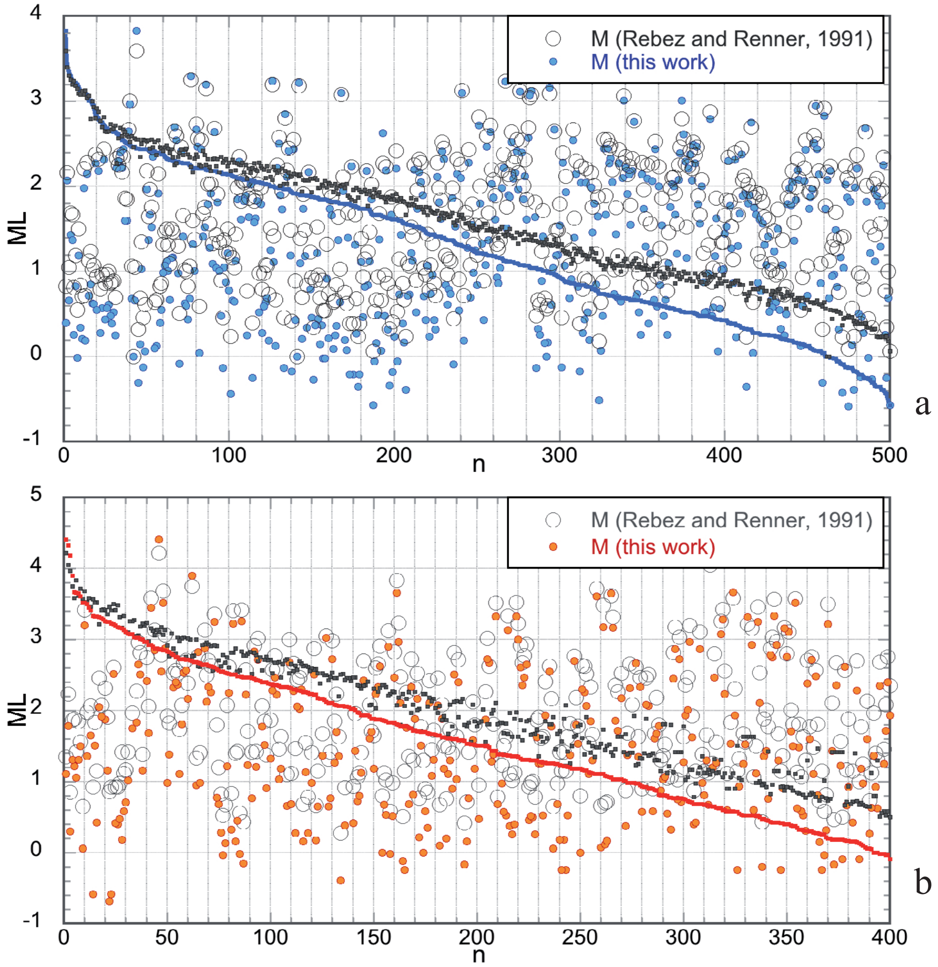

Fig. 8 - Magnitude values plotted in sequential order obtained by applying the Rebez and Renner (1991) formula (grey circles) and applying our new formula (filled blue circles); the same values with the same colours are superimposed in a descending magnitude (by Eq. 1) sorted order: a) for the year 1985; b) for the year 2013.

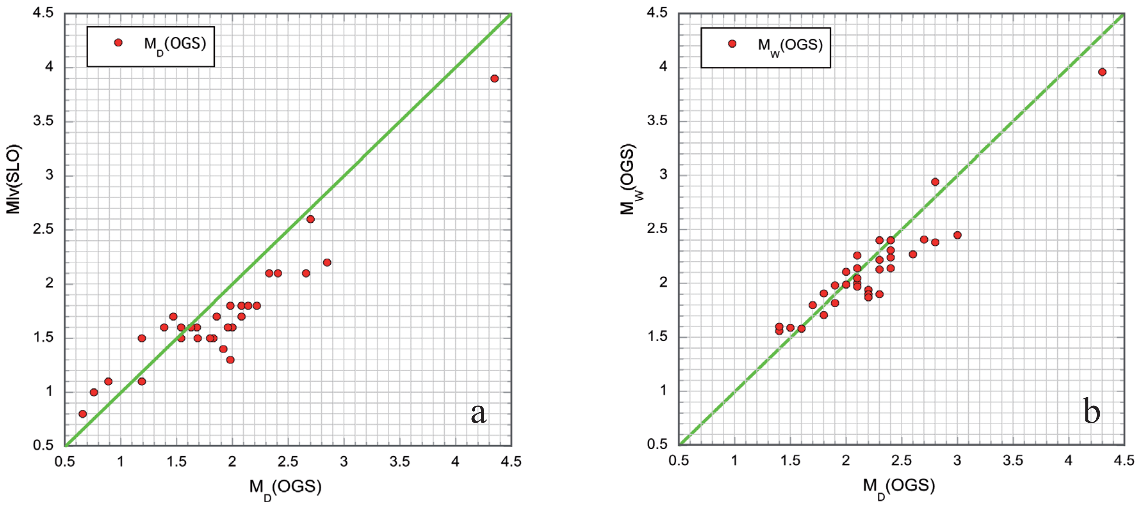

Fig. 9 - Comparisons of $M_D$ obtained by applying the new station formulae in Table 1 with other available magnitudes: a) with $M_{lv}$ by the Slovenian ARSO agency; b) with $M_W$ by Moratto *et al.* (2017).

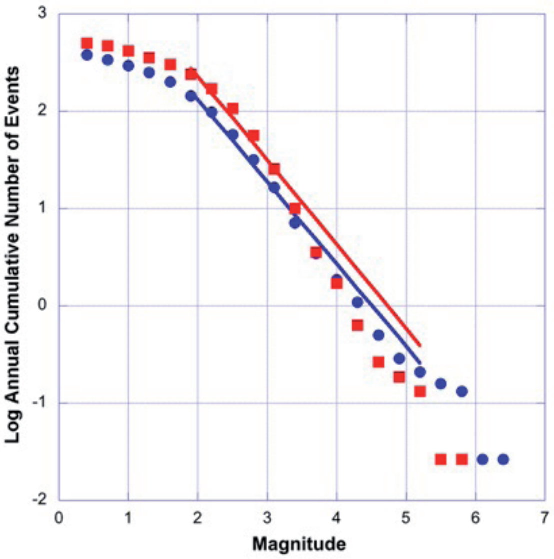

Fig. 10 - Gutenberg – Richter relationships for the OX data set (20,000 events from 1977 to 2014) considering the Rebez and Renner (1991) formulae (red squares and red line) and those introduced in this study (blue dots and blue line). The regressions have been done with the Maximum Likelihood method (Weichert, 1980). The obtained $b$-values are 0.86 and 0.85 with the Rebez and Renner (1991) and new formulae, respectively.

data sets obtained by the two sets of formulae. As expected, the annual seismicity rates computed with the new formulae (blue dots) are lower than those with the old ones (red squares) for $M_L$<4 and higher for large values. Surprisingly, the $b$-value remains almost constant at the value 0.86 with the existing formulae and 0.85 with the new ones.

## References

Bilal M. and Askan A.; 2014: *Relationships between felt intensity and recorded ground-motion parameters for Turkey*. Bull. Seismol. Soc. Am., **104**, 484-496, doi: 10.1785/0120130093.

Bisztricsany E. A., 1958: *A new method for the determination of the magnitude of earthquakes. Geofiz. Kozl.*, **7**, 69-76.

Carulli G.B. and Slejko D.; 2005: *The 1976 Friuli (NE Italy) earthquake*. Giornale di Geologia Applicata, **1**, 147-156.

Castello B., M. Olivieri M. and Selvaggi G.; 2007: *Local and duration magnitude determination for the Italian earthquake catalog, 1981–2002*. Bull. Seismol. Soc. Am., **97**, 128-139, doi: 10.1785/0120050258.

Cavallini F. and Rebez A.; 1996: *Representing earthquake intensity-magnitude relationship with a nonlinear function*. Bull. Seism. Soc. Am., **86**, 73-78.

Colautti D., Finetti I., Nieto D., Pupis C., Russi M., Slejko D. and Suhadolc P.; 1976: *Epicenter distribution and analysis of 1976 earthquakes and aftershocks of Friuli.* Boll. Geof. Appl., **18**, 457-548.

Finetti I. and Morelli C.; 1972: *Earthquake magnitude determination for Trieste WWSS station*. Boll. Geof. Teor. Appl., **14**, 67-83.

Finetti I., Russi M. and Slejko D.; 1979: *The Friuli earthquake (1976-1977)*. Tectonophysics, **53**, 261-272.

Gasperini P.; 2002: *Local magnitude revaluation for recent Italian earthquakes (1981-1996)*. J. Seismol. **6**, 503-524.

Gruppo di Lavoro CPTI (Boschi E., Gasperini P., Valensise G., Camassi R., Castelli V., Stucchi M., Rebez A., Monachesi G., Barbano M.S., Albini P., Guidoboni E., Ferrari G., Mariotti D., Comastri A. and Molin D.); *1999: Catalogo Parametrico dei Terremoti Italiani*. ING, GNDT, SGA, Bologna, 92 pp.

Lee W.H.K. and Lahr J.C.; 1975: *HYPO71 (revised): a computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes.* U.S. Geological Survey, Open file report, 75-311, Menlo Park, CA, USA, 113 pp.

Lee W.H.K., Bennet R. E. and Meaghu K. L.; 1972: *A method of estimating magnitude of local earthquakes from signal duration.* U.S. Geological Survey Open File Report, 1972, 28 pp.

Moratto L., Saraò A. and Priolo E.; 2017: *Moment magnitude ($M_W$) estimation of weak seismicity in northeastern Italy*. Seismol. Res. Lett., **88**, 1455-1464, doi: 10.1785/0220170063.

Priolo E., Barnaba C., Bernardi P., Bernardis G., Bragato P.L., Bressan G., Candido M., Cazzador E., Di Bartolomeo P., Durì G., Gentili S., Govoni A., Klinc P., Kravanja S., Laurenzano G., Lovisa L., Marotta P., Ponton F., Restivo A., Romanelli M., Snidarcig A., Urban S., Vuan A. and Zuliani D.; 2005: *Seisimic monitoring in north-eastern Italy: a ten-year experience.* Seis. Res. Lett., **76**, 446-454.

Real C. R. and Teng T.; 1973: *Local Richter magnitude and total signal duration in Southern California*. Bull. Seism. Soc. Am. **63,** no. 5, 1809-1827.

Rebez A., Renner G. and Slejko D.; 1984: *Calcolo della magnitudo locale da durata per la stazione sismologica di Trieste*. In: Finalità ed esperienze della Rete Sismometrica del Friuli-Venezia Giulia, Reg. Aut. Friuli-Venezia Giulia, Trieste, pp. 29-38.

Rebez A. and Renner G.; 1991: *Duration magnitude for the northeastern Italy seismometric network.* Boll. Geof. Teor. Appl., **33**, 177-186.

Renner G.; 1995: *The revision of the Northeastern Italy Seismometric Network catalogue*. Boll. Geof. Teor. Appl., **37**, Suppl. 1, 329 pp.

Richter C. F.; 1935: *An instrumental earthquake magnitude scale*. Bull. Seismol. Soc. Am. **25**, 1-32.

Richter C. F; 1958: *Elementary Seismology*. Freeman, San Francisco, Calif.. 578 pp.

Sandron D., Gentile G. F., Gentili S., Saraò A., Rebez A., Santulin M. and Slejko D.; 2015: *The Wood-Anderson of Trieste (Northeast Italy): One of the last operating torsion seismometers*. Seis. Res. Lett., **86**, doi: 10.1785/0220150047.

Slejko D.; 2018: *What science remains of the 1976 Friuli earthquake?* Boll. Geof. Teor. Appl., **59**, doi: 10.4430/bgta0224.

Slejko D., Rebez A. and Santulin M.; 2008: *Seismic hazard estimates for the Vittorio Veneto broader area (N.E. Italy)*. Boll. Geof. Teor. Appl., **49**, 329-356.

Soloviev S. L., 1965: *Seismicity of Sakalin*. Bull. Earth Res. Inst.,Tokyo Univ., **43**, 95–102.

Suhadolc P.; 1978: *Total durations and local magnitudes for small shocks in Friuli.* Boll. Geof. Teor. Appl. **20**, 303-312.

Tselenis G-A. and Danciu L.; 2008: *Empirical relationships between Modified Mercalli Intensity and engineering ground-motion parameters in Greece.* Bull. Seismol. Soc. Am., **98**, 1863–1875, doi: 10.1785/0120070172.

Tsumura K.; 1967: *Determination of earthquake magnitude from total duration of oscillation*. Bull. Earthquake Res. Inst., **45**, 7-18.

Weichert D.H.; 1980: *Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes*. Bull. Seism. Soc. Am., **70**, 1337-1346.

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