Relations between different kinds of magnitude determination and their regional variations*)

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Summary

It is shown that the determination of the so-called orthogonal regression is better suited than ordinary regression for a comparison of different kinds of magnitude determination and yields unique reversible relations. Many orthogonal regression relations have been determined and possible causes of the differences found are discussed. A great deal of discrepancies can be explained by differences in the method for measuring $(A/T)_{max}$ and by differences in the frequency characteristics of seismographs. The usefulness of some valid or recommended instructions for measuring $(A/T)_{max}$ is discussed and the importance of broad-band recordings is emphasized. Remarkable regional differences in the regression relations between magnitude determinations from short-period P-waves and long-period surface waves were found. They give a hint as to possible differences in the relative excitation and/or in the wave propagation of these two kinds of waves in different focal regions, which seem to correspond with seismotectonic and plate tectonic features. The magnitude dependence of the relation between MPV(A) and MLV or m_b and M_s, respectively, is explained by the scaling law of seismic spectra.

1. Introduction

It is well known that in general there are differences between magnitude values determined from different kinds of seismic waves as well as between those based on seismic records from instruments with different frequency responses. As an example we refer to the relation between the teleseismic body-wave (m_b) and surface-wave magnitude (M_s) given by GUTENBERG and RICHTER (1956) in the form

$$m_b = 0.63\ M_s + 2.5, \tag{1}$$

based on magnitude determinations from medium-period recordings, and to a corresponding relation given by GORDON (1971) as

$$m_b = 0.47\ (\pm\ 0.02)\ M_{s20} + 2.79\ (\pm\ 0.09), \tag{2}$$

based on short-period body-wave and long-period surface-wave recordings, respectively. Different authors (BUNE et al., 1970; KÁRNÍK, 1972; BORMANN, 1975) have shown that these "global" relations (i. e., relations based on data from all seismic regions in the distance range $10^\circ < D < 110^\circ$) can be reproduced with a high accuracy regardless of whether the relation is based on the magnitude data of a single station or on the mean magnitude values of a regional or global seismic network, provided that the types of instruments used are comparable. On the other hand, it has been shown in connection with

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identification problems by different authors (e.g., BASHAM, 1969; BORMANN, 1972) that there are indications of significant regional differences in these relations. A systematic study of these differences is to be one of the main points of this paper.

Another problem is the fact that the relations between different magnitude scales given in the relevant literature are usually calculated by means of the common regression analysis. This is only correct in the case of a one-dimensional random variable. As both magnitude values compared are affected by random errors, the so-called orthogonal regression is better suited to reveal the relation between the two random variables. The orthogonal regression yields an optimum estimate of the mean value if the random variables X_i and Y_i are symmetrically distributed (see, e.g., NAAS and SCHMID, 1961). In the given case this proposition is fulfilled, with some limitations, to a first approximation. The orthogonal regression relation is, contrary to the common regression relation, a unique reversible one. The difference between the two corresponding parameters b (as well as a) in the case of a linear regression $Y = a + b X$ can be considerable if the correlation coefficient ϱ is small (see Fig. 4).

The following investigations are based on magnitude determinations from Moxa station (MOX), using recordings by seismographs with standardized frequency characteristics (Fig. 1). As calibrating functions we have used the Q-functions of GUTENBERG and RICHTER (1956) for body-wave magnitudes and the so-called Prague calibrating functions (KÁRNÍK et al., 1962) for surface-wave magnitudes. Contrary to an earlier instruction of the WDC A, which suggests, for the calculation of m_b, to measure the maximum ratio A/T within the first five cycles of the short-period P-wave recording, we always determined the $(A/T)_{max}$ within the whole P-wave group. This maximum can arise in the case of strong multiple shocks up to about one minute after the first arrival (see, e.g., WYSS and BRUNE, 1967; BORMANN, 1969). The difference between the magnitude values determined from the first and the maximum P-wave arrivals, respectively, can amount to 1.5 magnitude units in short-period records (Fig. 2). In this connection we are of the opinion that the extension of the time interval for the measurement of $(A/T)_{max}$ up to 15 or 25 sec., as proposed by BUNE et al. (1973) and in the Report of the first meeting of the IASPEI Commission on Practice (1972), respectively, is not sufficient in all practical cases, especially not for the strongest earthquakes with $M > 7.5$, to find that P-wave magnitude which corresponds to the $(A/T)_{max}$ within the surface-wave group on which the M_s-determination always is based.

On the other hand, it is not correct to consider such a multiple event as one earthquake which can be described by one set of focal parameters such as the coordinates of its hypocentre, its focal time and its magnitude. In such cases we should determine the onset times and magnitudes of all clear successive P-wave onsets separately, as they give a first rough impression of the temporal and energetic development of the complex rupture process. The magnitude value $MP = \log \sum_n (A_i/T_i) + Q(D)$ (n is the number of successive P-wave onsets) could be considered as a more realistic measure of the P-wave energy released by such a multiple seismic event than the m_b-values determined from $(A/T)_{max}$ within the first 5 cycles or within the whole P-wave group.

The magnitude data of Moxa station are characterized as follows: The magnitude symbol M is followed by the phase symbol (P, PP, S, L), the abbreviation for the component (V - vertical, H - horizontal), and in parentheses the symbol of the standard type of frequency characteristic (A - short period, B - broad band, medium period, C - long period) from recordings for which the amplitude and period of ground motion have been evaluated. Magnitude data of NEIS (earlier NOAA and USCGS, respectively) from short-period P-waves and long-period surface waves are characterized as MB and MS, respectively.

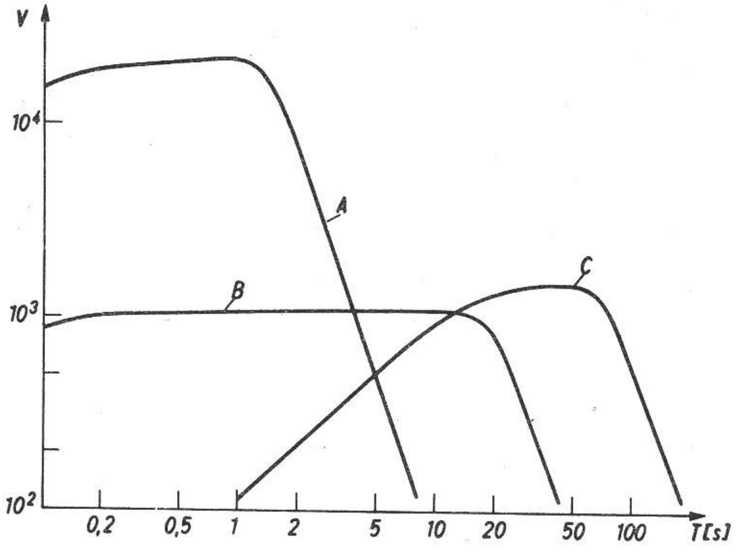


Fig. 1: Magnification curves of the standardized frequency characteristics of type A, B and C, respectively, in dependence on the period T of ground motion

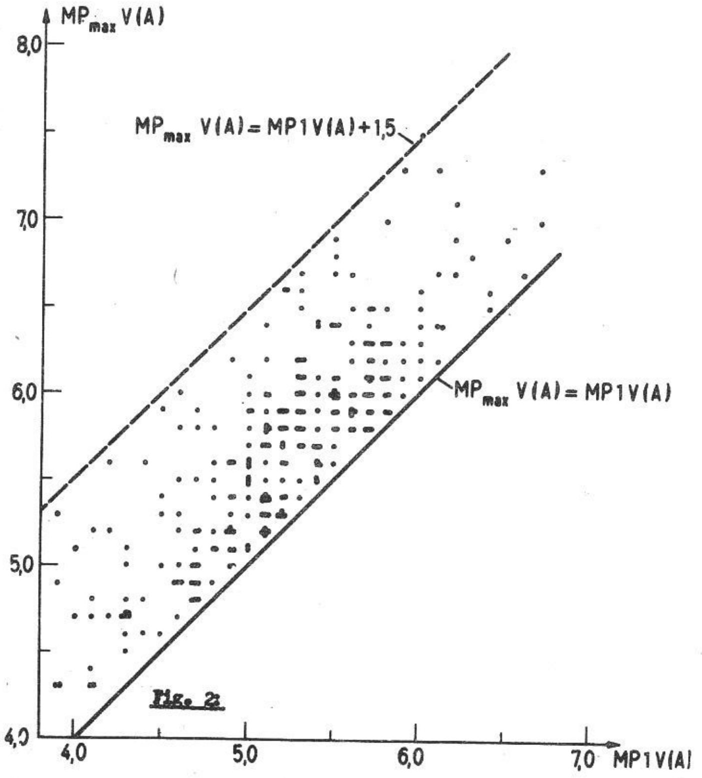


Fig. 2:

The relation between the magnitudes of the first and the maximum P-wave arrivals in the case of multiple P-wave groups in short-period records

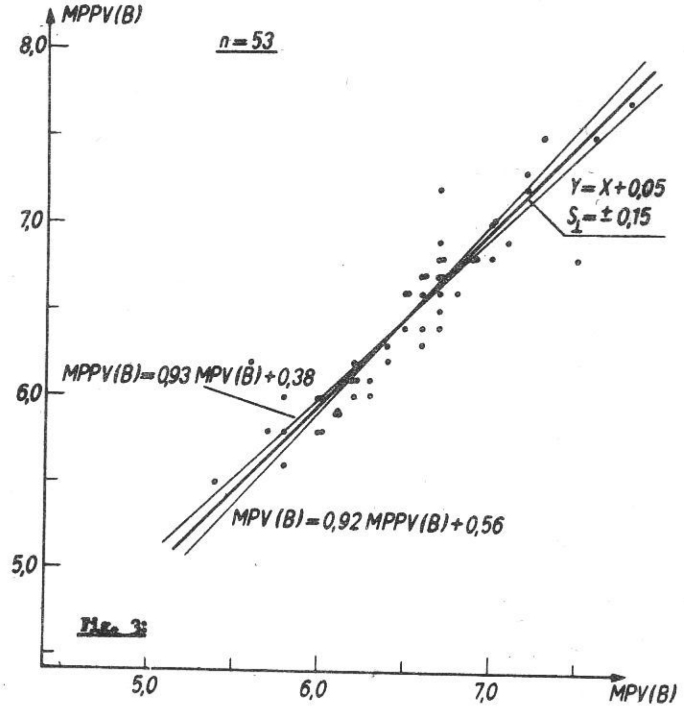


Fig. 3:

Regression relations between MPPV(B) and MPV(B). The equations MPPV(B) = b' MPV(B) + a' and MPV(B) = b' MPPV(B) + a", respectively, have been determined by the common regression analysis. Y = b X + a is the orthogonal regression line.

2. Orthogonal regression relations for global random tests

As shown by BORMANN and WYLEGALLA (1975), the body-wave magnitudes MPV, MPPV, and MSH as well as the surface-wave magnitudes MLV and MLH determined at a single station are nearly identical if broad-band records of type B are used (see Fig. 3). The corresponding b-values are in the interval $0.97 \leq b \leq 1.10$, the standard deviations from the orthogonal regression line amount to $0.1 < S_\perp < 0.2$, and the correlation coefficients are in the range $0.88 \leq \varrho \leq 0.98$. The best agreement is that between MLH and MLV. For the magnitude range $3.8 \leq M \leq 8.0$ we have obtained the relation

$$(3) \qquad \text{MLV} = 0.97\ \text{MLH} + 0.19$$

with $S_\perp = \pm 0.11$, $\varrho = 0.98$, $n = 1192$. This result shows that magnitude determinations from the vertical component of surface waves are of the same quality as those from the horizontal component. Up to now the surface-wave magnitudes MS given by the WDC's are based on the data of the horizontal component of surface waves only, although their evaluation is more complicated than for the vertical component.

The values for $S_\perp$ are significantly larger and those for ϱ much smaller if we compare the magnitudes determined from different kinds of short-period body-wave records for a single station (e.g., Fig. 4). KHALTURIN determined as standard errors of the magnitude determinations of the seismic services in the U.S.A. and U.S.S.R., respectively, S(MS) = S(MLH) = 0.15 for long-period surface waves and S(MB) = 0.31, S(MPV(A)) = 0.26, respectively, for short-period P-waves. The proposal of the IASPEI Commission on Practice to install a world-wide system of long-period high-gain seismographs to lower the threshold of MS-determinations is based on similar results. The greater scattering of magnitude data from short-period records is mainly due to non-regularities of the earthquake rupture process generating the main part of the short-period energy of the initial seismic pulse, and secondly, to the more intensive scattering of short-period seismic waves by small-size inhomogeneities along the propagation path.

The regression relation between MPV(A) and MLV(B) is of some interest in this connection. Fig. 5 clearly shows the non-linearity of this relation. The b-value decreases from b = 0.91 in the magnitude range $4.3 \leq \text{MLV} \leq 5.6$ to b = 0.45 for $6.0 \leq \text{MLV} \leq 8.2$. KHALTURIN obtained a similar result comparing the values of MPV(A) and MLH determined by the U.S.S.R. seismic service. His corresponding b-values decrease from b = 1.0 for the magnitude range $4.0 \leq \text{MLH} \leq 5.0$ to b = 0.4 for $6.0 \leq \text{MLH} \leq 7.5$. This decrease is more considerable for P-wave magnitudes determined from short-period narrow-band records than for those determined from broad-band and long-period ones. So KHALTURIN found a significantly smaller drop in the b-values from b = 1.0 in the magnitude range $4.6 \leq \text{MLH} \leq 5.8$ down to b = 0.64 for $6.3 \leq \text{MLH} \leq 7.8$ when comparing the MPV(B)- and MLH-data of the U.S.S.R. seismic service. This effect can be explained in terms of the scaling law of seismic spectra, derived by AKI (1967) on the basis of the dislocation theory. According to this scaling law, the increase of spectral amplitudes for a given increase of magnitude ΔM depends on the period and the magnitude level and is greater for long-period waves. From these statements it follows that the b-value of the orthogonal linear regression relation MPV(A) = a + b MLV has to decrease with increasing M.

Comparing the MLH-determinations of Moxa station with the corresponding MS-values given by NEIS for n = 162 earthquakes, we have obtained the relation

$$(4) \qquad \text{MS} = 0.88\ \text{MLH} + 0.52$$

with $S_\perp = 0.22$ and $\varrho = 0.90$.

KHALTURIN found a better agreement between the mean MS-values given by NEIS for the global station network and the mean MLH-values determined by the U.S.S.R. seismic service from the data for a regional system of seismographic stations in Eurasia (magnitude range $5.0 \le M \le 7.5$):

$$\text{(5)} \qquad MS = 1.00\ MLH - 0.15$$

with $S_\perp = 0.15$, $\varrho = 0.88$, $n = 687$. On an average, the MS-values are somewhat smaller than the corresponding MLH-values.

Finally, we have calculated the orthogonal regression relation

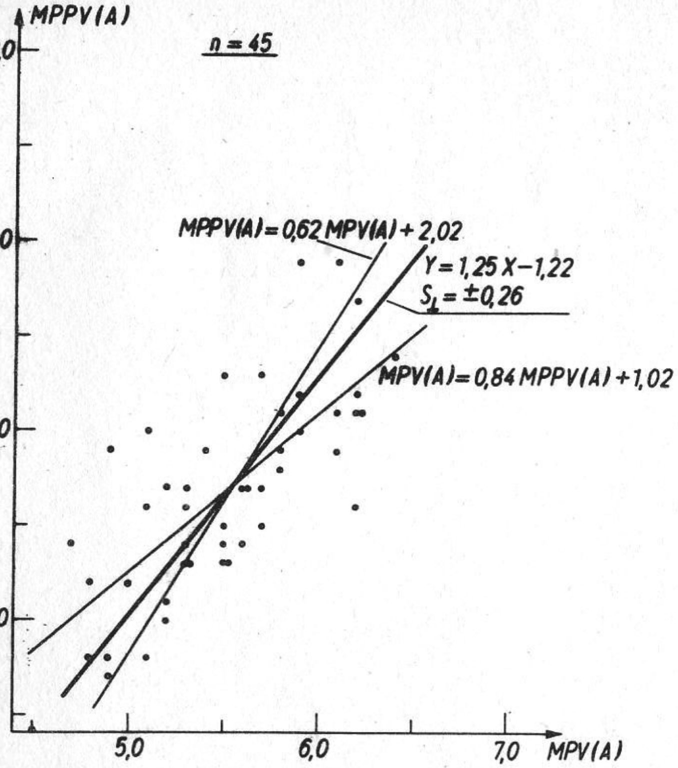
$$\text{(6)} \qquad MB = 0.88\ MPV(A) + 0.58,$$

where $S_\perp = 0.21$ and $\varrho = 0.80$ from $n = 3155$ short-period P-wave magnitudes determined by Moxa station and NEIS, respectively. The most surprising results are the almost identical equations (4) and (6) as well as the good agreement of the corresponding parameters $S_\perp$ and ϱ. Considering this fact, the capability of a world-wide system of long-period high-gain seismographs to substantially increase the accuracy of magnitude determinations seems to be doubtful. (Compare also the great regional differences of the MLH-MS relations as shown in 3.2.) KHALTURIN has determined the orthogonal regression relation

$$\text{(7)} \qquad MB = 0.94\ MPV(A) + 0.05$$

comparing 567 MB-determinations of NEIS with the corresponding MPV(A)-values of the U.S.S.R. seismic service. From (6) and (7) it follows that the mean MPV(A)-values of Moxa station are about 0.15 and those of the station network of the U.S.S.R. about 0.3 magnitude units greater than the MB-determinations from NEIS.

In this connection we want to draw again the attention to the often discussed systematic differences between the so-called "eastern" and "western" body-wave magnitudes (DAVIS, 1968; MARSHALL et al., 1972; DAHLMANN et al., 1974). At the U.S.S.R. stations medium-period seismographs with broad-band characteristics of type B and at WWNSS and array stations narrow-band short-period seismographs are usually used for MB-determinations. Narrow-band seismographs show a greater instrumental distortion compared to broad-band ones, which results in a stronger systematic diminution of the registration amplitudes for impulsive onsets (as expected from the magnification curves, which are valid for a stationary harmonic oscillation only!) (see, e.g., BORMANN, 1974). On the other hand, it follows from the seismic scaling law (see 2.) that with increasing magnitude the magnitude determinations from medium- and long-period records have to be greater than those from short-period ones. These two facts explain why the eastern body-wave magnitudes from broad-band records of type A and even more those of type B are up to about 0.6 magnitude units greater than the corresponding western MB-values, being a more realistic measure of the relative size of a seismic event. As a consequence of this fact, an extrapolation in low magnitudes using a magnitude/frequency relationship based on western MB-values will predict too many earthquakes. This explains some of the disagreements at the Geneva technical discussion in 1959 on banning nuclear tests (RIZNICHENKO, 1960; BORMANN, 1964; MARSHALL et al., 1972).



ig. 4: Regression relations between MPPV(A) and MPV(A) (for explanation see Fig. 3)

Fig. 5: A step-by-step calculation of the orthogonal regression lines in different magnitude intervals shows a clear magnitude dependence of the regression relations between the MPV(A)- and MLV-determinations of Moxa station for shallow earthquakes ($h \leq 70$ km). The parameters of the regression lines are:

1. $a = 0.51$, $b = 0.91$, $S_\perp = 0.25$; 2. $a = 1.53$, $b = 0.72$, $S_\perp = 0.28$; 3. $a : 3.32$, $b = 0.45$, $S_\perp = 0.29$

3. Orthogonal regression relations for different seismic regions

To study possible regional dependencies we calculated the orthogonal regression relations between different kinds of magnitude estimations for 24 different focal regions (BORMANN and WYLEGALLA, 1975). Some of the most significant results are given in what follows.

3.1. MLV - MLH

The regression analysis for MLV - MLH yielded nearly ideal relations (see Fig. 6) with almost no regional variation. The a- and b-values for all regions are within the ranges $-0.22 \leq a \leq +0.28$ and $0.95 \leq b \leq 1.04$, respectively. The correlation coefficients are extremely high ($0.96 < \varrho < 0.99$). This result also demonstrates the equivalence of MLV- and MLH-estimations.

3.2. MLH - MS

Fig. 7 shows that the relatively wide scattering of the data in (4) has to a great extent to be attributed to systematic regional differences of the MLH-MS relations for Moxa station up to about 0.8 magnitude units. These differences may be partly caused by the effect of lateral velocity and structural variations in the near-station region (azimuth-dependent station correction for magnitude determinations; see, e.g., WALZER, 1966) or along the main part of the propagation path (e.g., LAZAREVA and YANOVSKAYA, 1975; GREGERSEN and ALSOP, 1974). On the other hand, azimuthal variations of the energy radiation from the source have also to be taken into account. In the given case the main stress axes are oriented almost perpendicular to each other in the Taiwan-Ryukyu and Indonesia earthquake regions, respectively. Relatively great azimuthal differences of the surface-wave amplitudes can also be expected from this fact. The identification, separation and quantitative evaluation of all these possible effects is very complicated and has to be investigated in more detail in a later study.

In this connection it is interesting to remark that also KHALTURIN determined, from the data used in the global equation (5), two rather different regional regression relations:

(8) $\quad$ MS = MLH - 0.3

with $S_{\perp} = 0.19$ for earthquakes in the NW- and N-Pacific belt (Japan, Kurile Islands, Kamchatka, Aleutian Islands, Alaska) and

(9) $\quad$ MS = MLH

with $S_{\perp} = 0.14$ for earthquakes in the W- and SW-Pacific belt (Indonesia, Philippines, New Guinea, Fiji Islands).

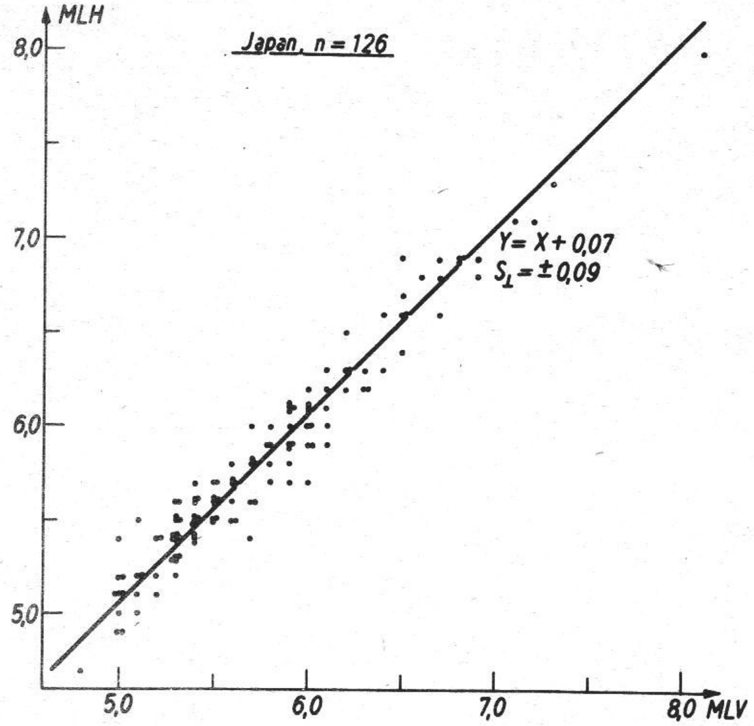


Fig. 6: Orthogonal regression relation between the MLV- and MLH-determinations of Moxa station for Japanese shallow earthquakes

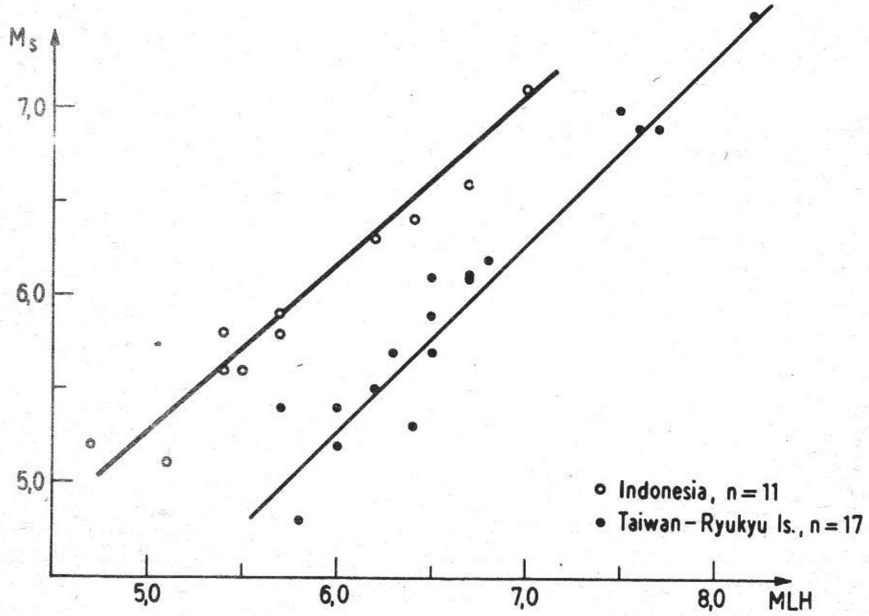


Fig. 7: Orthogonal regression relations between the MLH-determinations of Moxa station and the corresponding MS-values of NEIS for two different seismic regions

3.3. MPV(A) - MLV

Fig. 8 shows some orthogonal regression relations MLV = a + b MPV(A) for different regions. It reveals remarkable differences especially for greater values of M. For MPV(A) = 7 the differences between the corresponding mean values of MLV amount to 1.4 magnitude units. Another surprising result was the similarity of the b-values of some geographically connected regions. For instance, all b-values of the regions belonging to the Alps-Himalaya mountain belt in a distance range between 10° and 100° from Moxa station are within the interval $1.22 \leq b \leq 1.28$. The seismotectonic conditions are similar in these regions (orogene and deep faulting zones, almost only shallow earthquakes). Aleutian earthquakes show the lowest b-value ($b = 1.17$) and unusually small surface waves at Moxa station (MPV(A) = MLV on an average). Contrary to this, the Philippine Islands and Taiwan-Ryukyu Islands region respectively have extremely high b-values ($b = 1.80$ and 1.67). They are clearly different from the b-values for the regions Mariana Islands, Japan, and Kurile-Islands—Kamchatka, respectively ($b = 1.31$, 1.35, and 1.42). In this connection it is of interest to remark that the last mentioned seismic regions belong to the convergenee or subduction zone of the NW part of the main Pacific plate, whereas the earthquakes of the Philippine and Taiwan-Ryukyu Islands belong to the convergence zone of a subplate. It could be possible that the different plate-tectonic situation of the above-mentioned seismic regions involves differences in the relative excitation of short-period body-wave and long-period surface-wave energy as a function of M. On the other hand, we found for neighbouring regions remarkably constant mean differences in the MPV(A)- and MLV-values. For instance, the surface-wave magnitudes of Japanese earthquakes are for equal values of MPV(A) on an average 0.3 magnitude units greater than those of Mariana earthquakes, and for North America between 0.3 and 0.5 magnitude units greater than for earthquakes in Central and South America. Such constant mean differences can reflect regional variations of the attenuation properties of the crust and upper mantle in the focal region (see, e.g., BARAZANGI et al., 1975) or can be connected with causes discussed in 3.2. as azimuthal differences in the energy radiation and/or in the propagation for the two kinds of waves compared in the far- or near-station range.

3.4. MB - MPV(A)

The last problem considered is that of regional variations of the regression relations between the short-period P-wave magnitudes determined by NEIS and those of Moxa station. The regional differences of the MB-MPV(A) relations are unexpectedly high for strong earthquakes (Fig. 9). They amount to 0.8 magnitude units for MB = 7.0. Again, the b-values for magnitude data of shallow earthquakes in the alpine orogene belt are nearly identical ($0.69 \leq b \leq 0.72$) (region 4 excluded) and the b-values for the earthquake regions of the NW- and N-Pacific belt show a systematic clockwise increase from $b = 0.75$ for the Philippines to 1.16 for the Aleutians. But the most interesting result are the remarkable differences found between the correlations MB - MPV(A) for shallow and deep earthquakes in Central Asia ($b = 0.72$ and 0.53 respectively) as well as for earthquakes and underground nuclear explosions in the western U.S.A. (Fig. 10). Both differences seem to be connected with systematic differences in the P-wave spectra of these two kinds of seismic events in the regions mentioned on the one hand and with the differences in the standardized frequency characteristics of the short-period seismographs installed at the WWNSS-stations and Moxa station (Fig. 1) on the other.

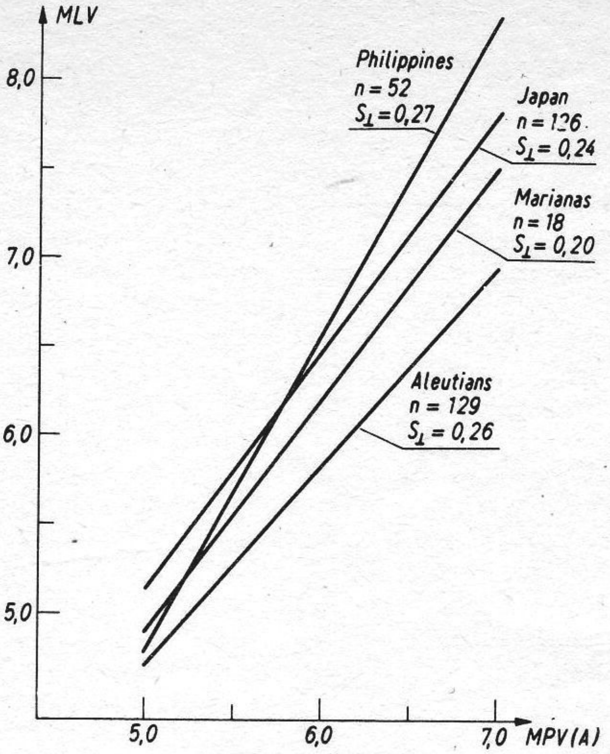


Fig. 8: Orthogonal regression lines for the MPV(A)–MLV data of Moxa station from shallow earthquakes in different regions

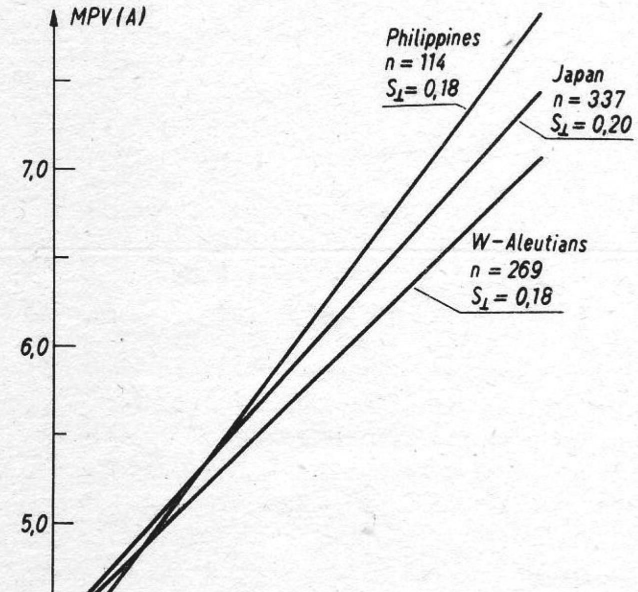


Fig. 9: Orthogonal regression relations MB – MPV(A) for earthquake regions in the NW-Pacific seismic belt

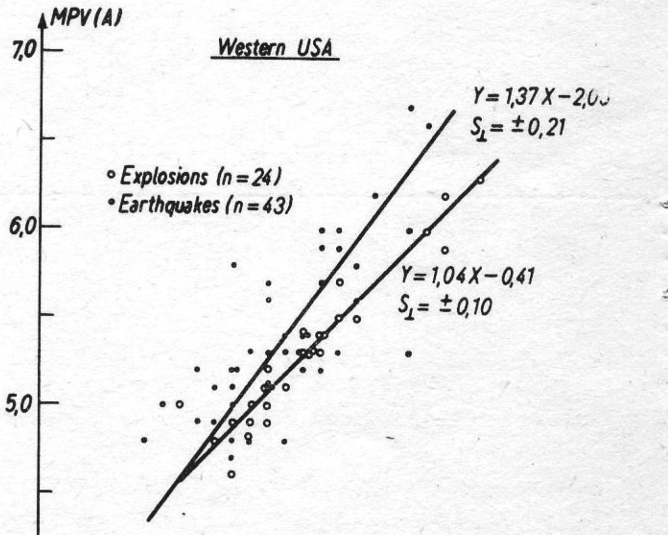


Fig.10: Orthogonal regression relations between the MB – MPV(A) data for earthquakes and underground nuclear explosions in the western U.S.A.

4. Conclusions

1. For converting one kind of magnitude data to another we can use the relations calculated by the common regression analysis as usually given in the relevant literature. But we always have to consider that we can apply these relations only in the given form. This is not uniquely reversible!
2. For a comparison of the regression relations between different kinds of magnitudes and a systematic study of their regional variations, orthogonal regression relations or a maximum likelihood of the data (see, e.g., ERICSSON, 1974; KUMMEL, 1879) should be used.
3. To reduce the systematic differences between magnitude determinations from body waves and surface waves, short-period or medium-period broad-band records should be preferred to short-period narrow-band ones for the MB-determination and the time interval for measuring the maximum value of A/T should be extended to about 1 minute for the strongest earthquakes.
4. In the case of a multiple shock we should determine the onset times and magnitudes of all clear successive P-wave (and S-wave) onsets separately as they give a rough impression of the temporal and energetic development of the complex rupture process. As a more realistic measure of the whole P-wave energy released by such a multiple event the value $\lg \sum_{n} A_i/T_i$ should be used in the determination of MPV (n is the number of successive P-wave onsets).
5. The comparison of the magnitude determinations of Moxa station from long-period surface waves and short-period P-waves, respectively, with the corresponding values MS and MB of NEIS shows similar data scattering and regional variations. From this surprising result there follow some problems concerning the utility of a world-wide system of long-period high-gain seismographs for substantially increasing the accuracy of magnitude estimations.
6. Since the agreement betwзen the corresponding MLV- and MLH-values of earthquakes is practically ideal, we propose to include the MLV-data in the MS-calculations of the WDC's.
7. According to the seismic scaling law the regression relations between magnitude determinations based on seismographic records in different frequency bands (e.g., the relation between MB and MS) depend on the magnitude. Therefore, any study of regional differences in these relations has to compare the data in the same magnitude interval.
8. Significant regional differences in the relations MPV(A) – MLV were found. They indicate regional and/or azimuthal differences in the relative excitation and/or propagation of these two kinds of waves.
9. The differences between the so-called "eastern" and "western" body-wave magnitudes discussed in literature can be explained as an effect of different distortions of impulsive onsets and as a consequence of the seismic scaling law by using seismographs with different types (pass bands) of frequency characteristics.

Acknowledgement and remarks

The magnitude data of the years 1965 to 1967 for Moxa station were evaluated by one of the authors (P. BORMANN) himself. Most of the magnitude values for Moxa station used in our analysis for the years 1968 to 1971 are based on evaluations by the seismological service of the Central Earth Physics Institute at Jena. We are very indebted to Mr. J. STELZNER, chief of the seismological service, and to his colleagues Miss D. GÜTH and Mr.

J. WEYRAUCH for throwing their data open for use in our analysis. A test has shown that there are no systematic deviations between the magnitude determinations carried out by the above author and those of the colleagues mentioned.

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