Calibration of Local Magnitude Scales For Use in Seismic Monitoring

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Abstract

In situations where cavity decoupling is a plausible evasion scenario, comprehensive monitoring of any eventual CTBT will require the routine identification of many small seismic events with magnitudes in the range $2.0 < m_b < 3.5$. Thus, an important issue in the assessment of monitoring requirements concerns the definition of the numbers and types of events which will generate seismic signals in this magnitude range. This has proved to be a difficult question to answer with any real degree of confidence, because the magnitude values reported for most small events are based on a variety of regional magnitude scales which may not be consistent with the teleseismic m_b magnitude scale which is used to specify seismic monitoring capability. Under this project, we are attempting to quantitatively relate such regional magnitude measures to m_b. This is being accomplished by theoretically scaling observed regional seismic data recorded from tamped underground nuclear tests to obtain estimates of the corresponding seismic signals to be expected from small cavity decoupled nuclear explosions at those same source locations. These synthetic data are processed to determine various local magnitude measures which can then be directly correlated with the known m_b values of these synthetic explosions. This theoretical scaling procedure has now been applied to regional seismic data recorded at the Scandinavian NORESS and ARCESS arrays from tamped Soviet nuclear explosions at the Novaya Zemlya and selected PNE sites and to data recorded at IRIS stations from explosions at the Semipalatinsk and Lop Nor test sites. Results of analyses of these synthetic data indicate that, even for the well-calibrated Scandinavian arrays, regional magnitude measures can show a pronounced dependence on source location and type. For example, since regional magnitude scales are typically calibrated using data recorded from small earthquakes and mine blasts, differences between explosion and earthquake regional phase characteristics, such as the L_g/P ratio, can lead to consistent bias in regional magnitude determinations for explosions. Analyses of the phase and frequency dependence of such biases are currently being conducted in an attempt to define an optimum regional magnitude measure for use in seismic monitoring.

Key Words: Seismic, Magnitude, Regional, Explosion, Cavity Decoupling

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Objective

A central issue in current discussions of the seismic monitoring capability required to adequately verify any eventual Comprehensive Test Ban Treaty (CTBT) concerns the definition of the threshold level of seismic event size or magnitude down to which seismic events will have to be detected and identified. It is generally agreed that the capability currently exists to unambiguously identify almost all seismic events having magnitudes characteristic of well-coupled underground nuclear explosions with yields greater than a few kilotons (i.e., $m_b \sim 4$, OTA (1988)). However, in the context of monitoring a CTBT, consideration has to be given to the requirement to characterize the much smaller signals which would be expected to result from various evasive testing practices which might be employed by a nation pursuing a clandestine nuclear weapons development program. For example, since it has been experimentally demonstrated that it is possible to reduce the amplitude of the radiated seismic signal of an underground nuclear explosion by at least a factor of 70 by employing the cavity decoupling evasion scenario, it follows that comprehensive monitoring of underground nuclear tests in the 1 to 10 kt range will necessarily involve identification analyses of small seismic events with magnitudes in the range $2.0 < m_b < 3.5$. However, since such small events are generally not recorded teleseismically, their magnitudes are typically determined using one of the many proposed regional magnitude scales (M_L). This constitutes a problem in that such regional magnitude measures are defined in terms of seismic phases and frequency bands which are different from those associated with the traditional teleseismic m_b magnitude measure and, consequently, it is not always clear how they relate to the corresponding m_b values which are used to specify seismic monitoring capability. The objective of this project has been to attempt to develop an improved quantitative understanding of the relationship between M_L and m_b for small underground nuclear tests. This has been accomplished through analyses of synthetic data obtained by theoretically scaling observed regional seismic data recorded from tamped underground nuclear tests to obtain estimates of the corresponding seismic signals to be expected from small cavity decoupled nuclear tests at those same source locations.

Research Accomplishments

The scaling procedure used to derive the synthetic regional seismic data analyzed in this study has been described in detail by Murphy and Barker (1994). In this approximation, if the elastic radius of the seismic source of the tamped reference explosion of yield W_T is denoted as rel_2, then the elastic radius for the corresponding cavity decoupled explosion is

$$rel_1 = \frac{rel_2}{(DF)^{1/3}}$$

where DF denotes the decoupling factor for a particular yield/cavity volume ratio. For each selected tamped explosion we have considered a range of decoupling factors which increase incrementally by factors of 2 such that DF = 2,4,8,..., 70 W_T where 70 W_T corresponds to the case of 1 kt fully decoupled with a low frequency decoupling factor of 70. Now, for values of $W_T < 100$ kt, the corner frequency of the tamped explosion source generally lies above 1 Hz and, consequently, the m_b values corresponding to such a sequence of partially decoupled synthetic explosions can be approximated simply as

$$m_{bi} = m_b(T) - \log(2,4,8,..., 70\ W_T)$$

where $m_b(T)$ is the observed m_b value of the tamped explosion with yield W_T. A typical sequence of such source spectrum scaling operators is shown in Figure 1 for the Soviet JVE event, where a nominal seismic yield of about 115 kt has been used for that explosion. It can be seen from this figure that the scaling is strongly frequency dependent over this regional band extending from 0.1 to 20 Hz, particularly for the operators corresponding to the lower yield decoupled explosions. Not surprisingly, such frequency dependent scaling can have some pronounced effects on the characteristics of the corresponding broadband regional seismograms. This is illustrated in Figure 2 which shows the results of scaling the IRIS station GARM recording of the Soviet JVE (Δ = 1380 km) using the range of source scaling operators from Figure 1. It can be seen that in this case the lower frequency L_g and R_g signals are progressively attenuated with respect to the higher frequency P signals as the data are scaled to lower m_b values. Clearly, such large variations in relative phase amplitudes can be expected to have pronounced effects on at least some regional magnitude measures.

The sample of tamped underground nuclear explosions for which regional seismic data were scaled using the above procedures is summarized in Table 1. It can be seen that the first two events in Table 1 were recorded at the ARPA array stations ARCESS and NORESS in Scandinavia, for which extensive magnitude calibration studies have been carried out, leading to a regional magnitude measure which is expressed as a weighted average of individual phase magnitudes determined from measured amplitudes of the P_n, P_g, S_n and L_g arrivals (Bache et al., 1991). The individual phase magnitudes for the scaled

Table 1
Tamped Explosion Data Sample

Event		Station	Estimated Yield, kt	Δ, km
Novaya Zemlya	10/24/90	ARCESS	65	1110
PNE (Archangel)	7/18/85	NORESS	8.5	1564
Soviet JVE	9/14/88	WMQ	115	950
Soviet JVE	9/14/88	GARM	115	1380
Soviet JVE	9/14/88	ARU	115	1530
Lop Nor	8/16/90	GARM	215	1590

Novaya Zemlya 10/24/90 explosion recordings at ARCESS determined using these algorithms are plotted as functions of m_b in Figure 3 where the corresponding $M_L = m_b$ nominal relations are also shown for reference purposes. It can be seen that these individual phase magnitude values show some significant divergences from the expected $M_L = m_b$ relations, with the P_n and S_n values biased high by about 0.6 magnitude units and the L_g values biased low by about 0.4 magnitude units for the smaller events. This broad scatter is presumably due to the fact that the propagation path from Novaya Zemlya to ARCESS is quite different from those of the regional earthquakes and mine blasts used to calibrate the ARCESS magnitude determination algorithms. This example graphically illustrates the fact that, even for well calibrated stations, significant biases can occur for events in locations not represented in the calibration database. Another notable feature illustrated by Figure 3 is the tendency for the explosion Lg magnitudes to be lower than those determined from the other phases. This has been found to be a consistent result of the study, even for well calibrated propagation paths. This fact is illustrated in Figure 4 which shows the various magnitude measures determined from the scaled recordings of Table 1, evaluated at a fixed m_b value of 3.0. Note from the left panel of this figure that the L_g magnitude is lower than the others, even for the well calibrated PNE to NORESS path. It seems likely that this consistent bias is due to differences in the relative phase excitation levels associated with the different source types. That is, since the magnitude determination algorithms are generally calibrated using earthquake and mine blast data, it can be expected that the L_g magnitudes will be biased low for explosion sources due to characteristic differences in the average L_g/P amplitude ratios for these different source types. The right hand panel of Figure 4 illustrates the range of variation in regional phase characteristics for explosions recorded along selected paths in Central Asia. In these examples, the individual phase magnitudes were again estimated using the Scandinavian algorithms to provide a constant reference base and, consequently, it can be expected that careful path calibration studies could be expected to significantly reduce the variability displayed here. However, these results do serve to emphasize once again the very strong dependence of regional phase characteristics on the properties of the propagation paths. Analyses of the phase and frequency dependence of such biases are continuing in an attempt to define a more optimal regional magnitude measure for use in seismic monitoring.

Conclusions and Recommendations

The definition of meaningful magnitude measures for small seismic events remains as a major unsolved issue affecting assessments of CTBT monitoring requirements. That is, since such events are not expected to be detected teleseismically, their magnitudes will have to be estimated from regional recordings using seismic phases and frequency bands which are different from those employed in the teleseismic m_b scale which is generally used to specify seismic monitoring capability. In this study, we have attempted to quantitatively relate these different magnitude measures by theoretically scaling regional seismic data observed from tamped underground nuclear explosions to obtain improved estimates of the corresponding signals to be expected from low yield cavity decoupled explosions at a variety of different source locations. Analyses of these synthetic data have indicated that, even for well calibrated stations such as the ARPA Scandinavian arrays, traditional regional magnitude measures can show a pronounced dependence on source type and location. In particular, it has been demonstrated that differences between explosion and earthquake regional phase characteristics, such as the average L_g/P ratio, can lead to consistent biases between regional magnitude estimates for explosions and earthquakes having comparable m_b values. Such biases and associated uncertainties should be carefully considered in the definition of required magnitude monitoring thresholds for any eventual CTBT.

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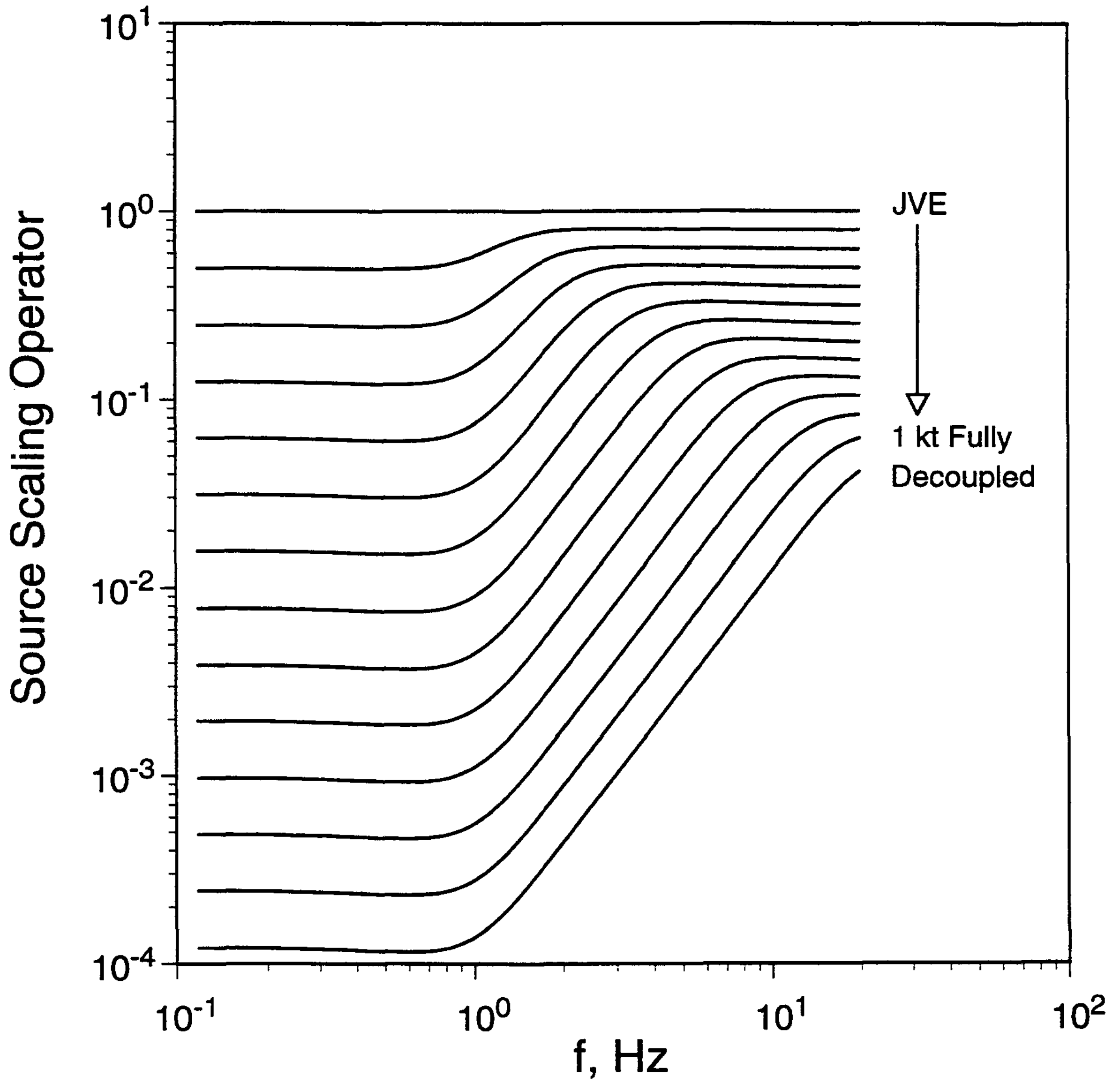

Figure 1. Frequency dependent source scaling operators used to theoretically scale observed regional recordings from the Soviet JVE to simulate the signals expected from various cavity decoupling scenarios.

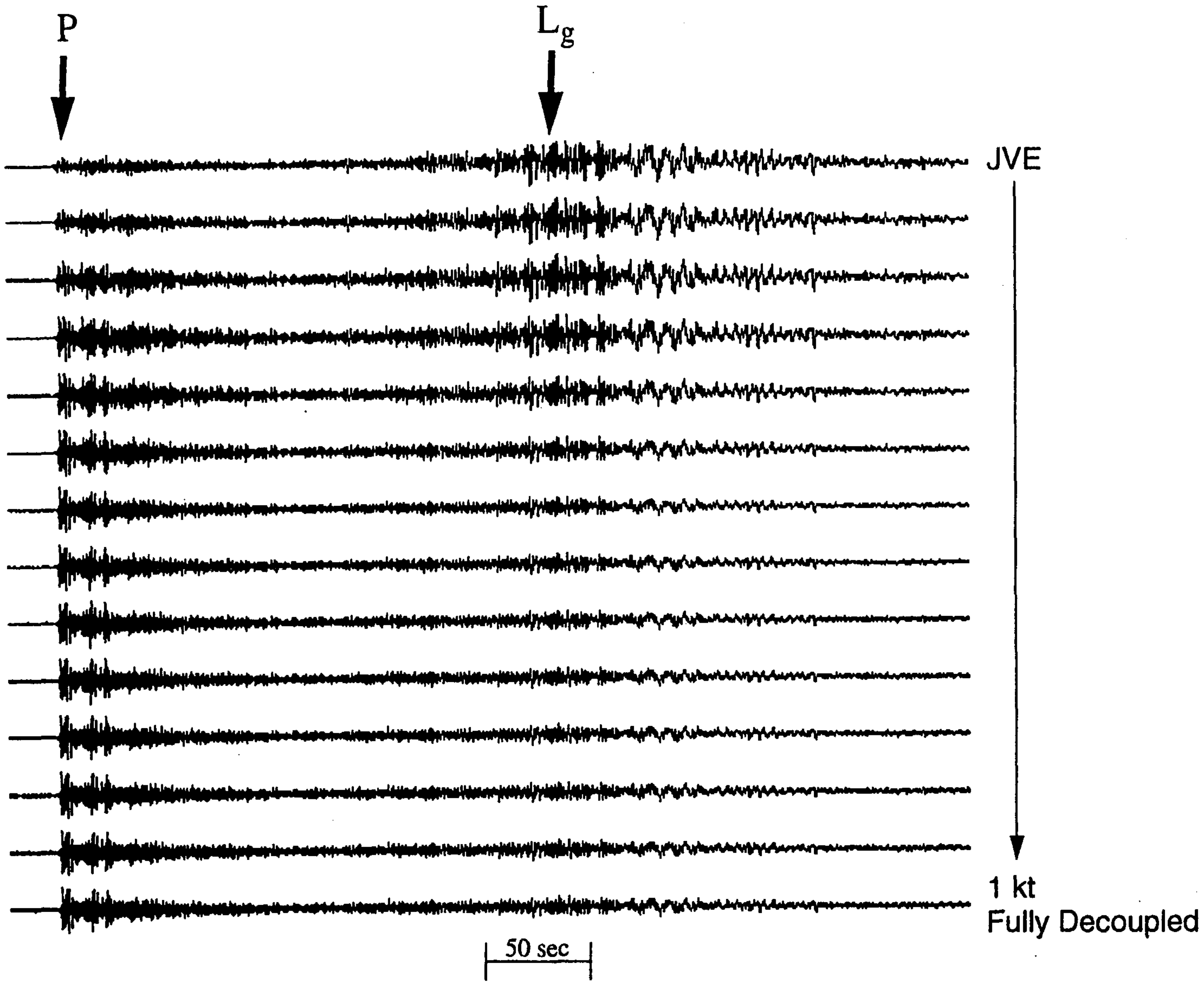

Figure 2. Synthetic cavity decoupled regional seismograms obtained by applying the theoretical source scaling operators of Figure 1 to the IRIS station GARM ($\Delta = 1380$ km) recording of the Soviet JVE.

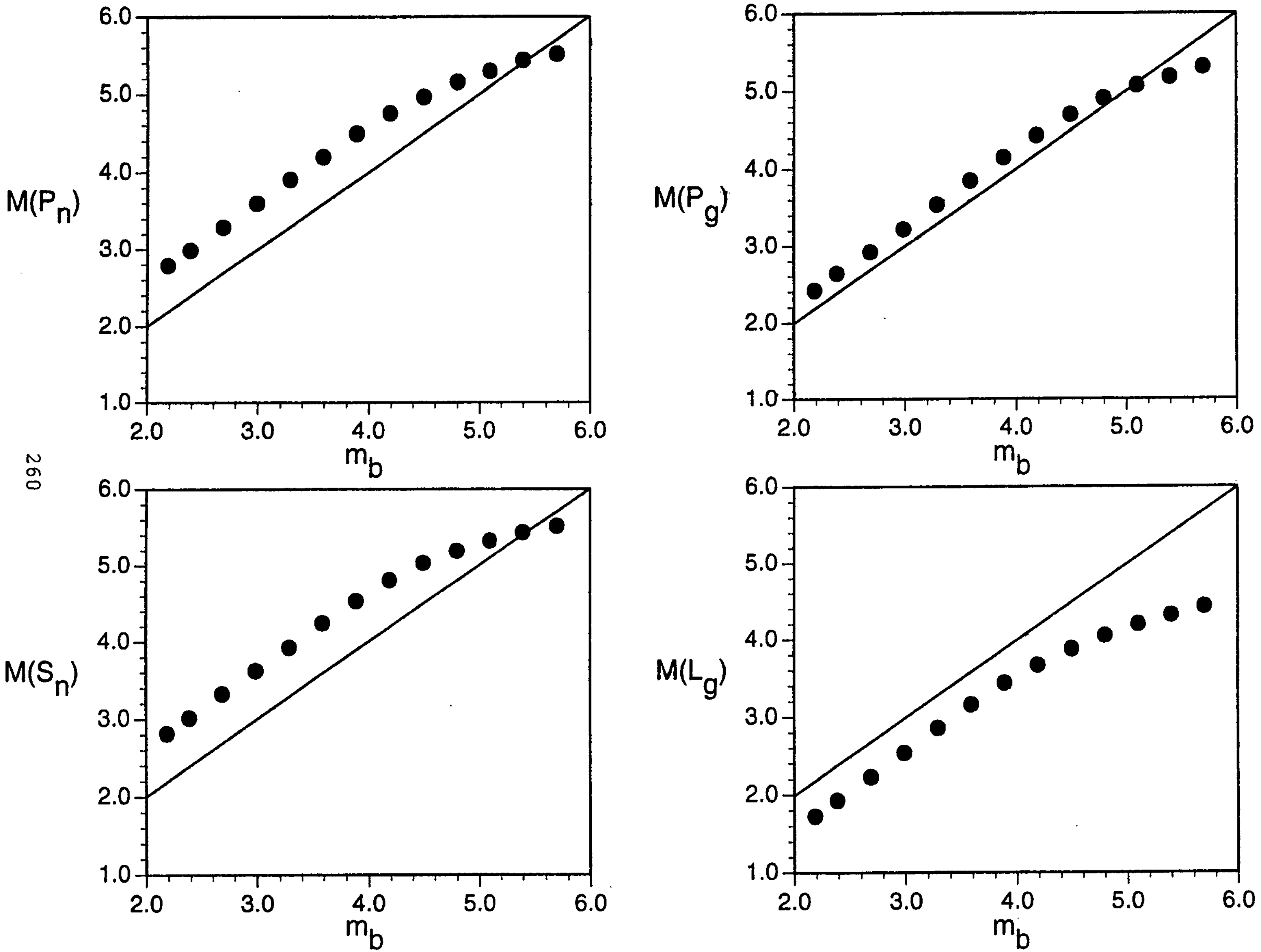

Figure 3. Regional seismic magnitudes as functions of m_b derived from source scaled versions of the ARCESS recording of the Novaya Zemlya nuclear explosion of 10/24/90.

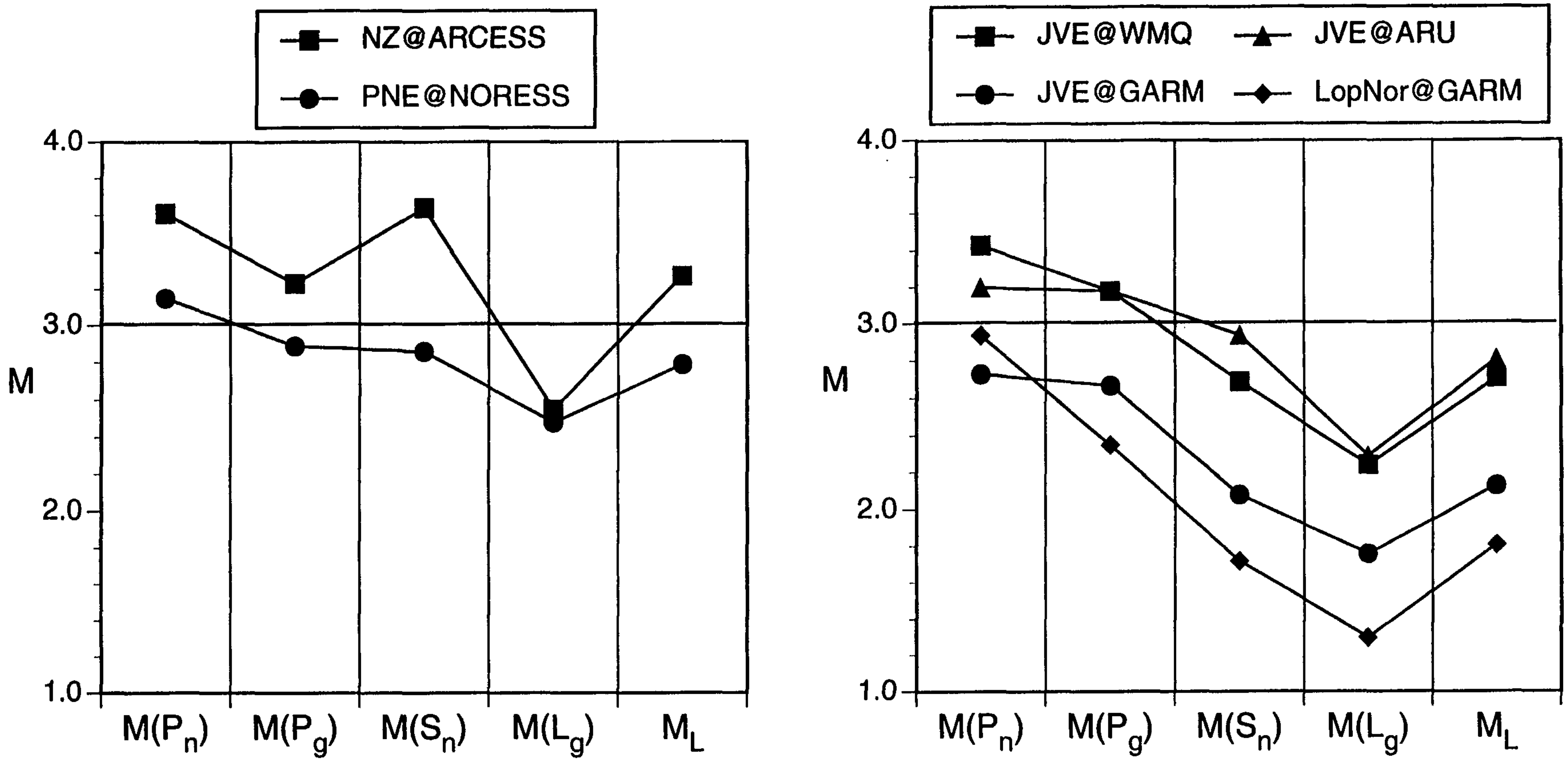

Figure 4. Variations of regional seismic magnitude measures for $m_b = 3.0$ explosions in Scandinavia (left) and Central Asia (right).