INVESTIGATIONS INTO REGIONAL MAGNITUDE SCALING: TRANSPORTABILITY AND M_s : m_b RELATIONSHIPS BASED ON NUTTLI'S m_b(Lg)

Howard J. Patton
Los Alamos Seismic Research Center
Earth and Environmental Sciences Division
Los Alamos National Laboratory

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ABSTRACT

Datasets of m_b(Pn) and m_b(Lg) measurements are presented for three continental regions to investigate magnitude scaling and issues related to event discrimination at small magnitudes. Compilations of published measurements are provided for eastern North America and central Asia, while new measurements are reported for earthquakes located in western United States, significantly increasing the number of previously reported m_b(Lg) and m_b(Pn) observations for this region. Transportability of regional magnitudes between tectonic provinces is investigated by statistical tests of scaling relationships for all three regions. While m_b(Pn) failed these tests, the m_b(Lg) scale of Nuttli (1973) is shown to be transportable and scales similarly for earthquakes with M_w ~4.2 - 6.5 and nuclear explosions with M_w 3.5 - ~5.5. Below M_w 4.0, m_b(Lg) scales differently for earthquakes in eastern North America and western United States. Scaling coefficients for m_b(Pn) and m_b(Lg) have values near 1.0, scaling as ~ $2/3 \cdot \log M_o$ (seismic moment) based on linear regressions of earthquakes with M_w ~3.9 - 6.5. For nuclear explosions, m_b(Pn) scales at a significantly higher rate than m_b(Lg), and this could be related to differences in "effective" source functions for Pn and Lg waves. Observed differences in scaling coefficients can be explained by (1) over-shoot in the reduced displacement potential affecting Pn amplitudes and (2) generation of 1-Hz Lg by near-field Rg-to-S scattering.

M_w:m_b(Lg) scaling relationships are converted to M_s:m_b(Lg) using published scaling laws between log M_o and M_s. Explosions conducted in weak materials and releasing tectonic stress by strike-slip faulting lie ~0.4 m_b units closer to earthquakes than explosions conducted in hard rock with thrust tectonic release. M_s:m_b(Lg) relationships scale as 0.69 and 0.78 for earthquakes and explosions respectively. Earthquakes are separated from hard-rock explosions by 1 − 1.25 m_b units for M_s greater than ~3.0; for M_s 1.5, the separation is reduced to ~0.7 m_b units in stable continents. Estimates of m_b(P) bias are made by comparing M_s:m_b(P) observations with M_s:m_b(Lg) relationships derived in this study. Results of these comparisons for earthquakes suggest that m_b(P) bias is significant, averaging about −0.4 m_b units, for tectonic regions of southern Asia.

Key Words: Seismic magnitude, source scaling, discrimination, regionalization

OBJECTIVE

The objective of this work is (1) to develop regional magnitude scales for CTBT monitoring purposes, (2) to apply these scales in regions of interest, (3) to evaluate the performance of regional M_s:m_b discriminants at small magnitudes, and (4) to develop relationships between regional magnitudes and teleseismic m_b for the characterization of regional m_b bias.

M_s:m_b is an important discriminant with a long history of success in teleseismic applications and a firm physical basis. Application of M_s:m_b to small magnitude events requires extensions to regional data. It is highly desirable for regional magnitude scales to exhibit stability and robustness, to be effective at small magnitudes and over the entire regional distance range, and finally to be transportable. Transportability is a key feature because of the wide range of geologies and tectonics of monitoring environments. This work focuses on research and development necessary to assure successful extension of M_s:m_b to regional applications.

RESEARCH ACCOMPLISHED

The first part of this work focuses on the problem of transportability. Teleseismic magnitude m_b(P) has long been known to be non-transportable. A classic example is the western U. S., where seismologists have long known of differences between this region and eastern U. S., e.g., $m_b(P;west) \approx m_b(P;east) - 0.33$ (Chung and Bernreuter, 1981). Another example is from monitoring the Threshold Test Ban Treaty, where test site bias for the Nevada Test Site (NTS) and test sites of the former Soviet Union was an important issue. It was found that the NTS m_b(P) - yield curve for well-coupled shots does <u>not</u> apply to explosions at other test sites because m_b(P) is not transportable between test sites. In both examples, anomalous P-wave attenuation in the upper mantle under western U. S. is commonly accepted as the cause of non-transportability of teleseismic m_b (Douglas and Marshall, 1996).

A standard practice in developing regional magnitudes scales is the stage where the scale is “tied to” or “calibrated against” teleseismic magnitude. Since magnitude is an arbitrary construct, this practice simply puts the regional magnitude on the same “baseline” as m_b(P). Typically this calibration is performed on a region by region basis (for an example, see the paper on calibration of m_b(Pn) scale for western U. S. by Denny et al., 1987). It is important to note that a regional magnitude scale so calibrated will <u>not</u> be transportable because biases in m_b(P) data used for calibration will be transferred to the new scale by the calibration procedure.

The regional magnitude m_b(Lg) devised by O. Nuttli is tied to teleseismic m_b in central U. S. (Nuttli, 1973). In 1986, Nuttli applied a more generalized formulation of m_b(Lg), still tied to m_b in the central U. S., to NTS explosions for the purpose of improved yield estimation (Nuttli, 1986a). Subsequent studies were carried out to estimate m_b(Lg) for Soviet explosions detonated at test sites in Kazakhstan (KTS) and Novaya Zemlya (Nuttli, 1986b; 1987; 1988). In addition to their usefulness for yield estimation, measurements of m_b(Lg) provided a means for computing test site bias by direct comparison of m_b(P) and m_b(Lg) for explosions with both measurements. The important results in this series of papers required that $m_b(Lg)$ is transportable, an assertion Nuttli made repeatedly. Why should this scale be transportable and other regional scales are not?

Examining Nuttli's 1986 formulation, it can be seen that $m_b(Lg)$ is tied to $m_b(P)$ <u>once and only once</u> (for the central U. S., as mentioned above) by the calibration equation,

$$m_b(Lg) = 5.0 + \log_{10} [\ A(10) / 110.\ ],$$

where

$$A(10) = A(\Delta) \cdot (\Delta/10)^{1/3} \cdot [\sin(\Delta/111.1) / \sin(10/111.1)]^{1/2} \cdot \exp[\gamma \cdot (\Delta - 10)],$$

and Δ is epicentral distance, γ is attenuation coefficient, and "exp" is the exponential function. $A(\Delta)$ is Lg amplitude measured near 1 Hz off regional seismograms recorded on short-period WWSSN instrumentation. This amplitude is corrected for Airy phase propagation, geometrical spreading, and attenuation back to a reference distance of 10 km. The calibration equation states that *an earthquake in central U. S. with $m_b(P)$ 5.0 will produce a "hypothetical" 1-Hz Lg wave 10 km from the source of 110 microns amplitude.* For $m_b(Lg)$ to be transportable, two conditions must be met: (1) the hypothetical calibration amplitude of 110 microns is valid from one region to the next and (2) accurate path corrections for attenuation are available for Lg waves. Another way to state condition (1) above is that 1-Hz Green's function responses for Lg waves are invariant in continental structures and for seismogenic depths confined to the crust.

While Nuttli's results for nuclear explosions support his claim of transportability, the claim has never been tested rigorously on datasets of earthquakes located in structurally/tectonically diverse regions. In this study, I present the results of statistical tests for transportability comparing $m_b(P)$, $m_b(Pn)$ and $m_b(Lg)$ scaling relationships for earthquakes located in eastern North America (ENA), western U. S. (WUS), and central Asia (CA). The results confirm non-transportability of $m_b(P)$ and also demonstrate non-transportability of $m_b(Pn)$. However, $m_b(Lg)$ is transportable and scales similarly for earthquakes with M_w ~4.2 - 6.5 and for nuclear explosions with M_w 3.5 - ~5.5. Below M_w 4.0, $m_b(Lg)$ scales differently for ENA and WUS.

Figure 1a summarizes $m_b(Lg)$ observations for all earthquakes and all nuclear explosions analyzed in this study. The nuclear explosions were detonated at continental test sites around the world in a wide variety of emplacement conditions. Regression lines are shown for 1st-order scaling models (there is no evidence for magnitude saturation of $m_b(Lg)$ for events in this dataset up to M_w 6.5). Earthquake scaling in stable regions is based on data for ENA, while scaling in tectonic regions is based on WUS and CA data. The "unified" M_w:$m_b(Lg)$ scaling relationship was derived using earthquake data from all three regions for M_w 4.2 - 6.5, and it is arguably transportable to any continental region. Also shown in Figure 1a is the scaling relationship for nuclear explosions.

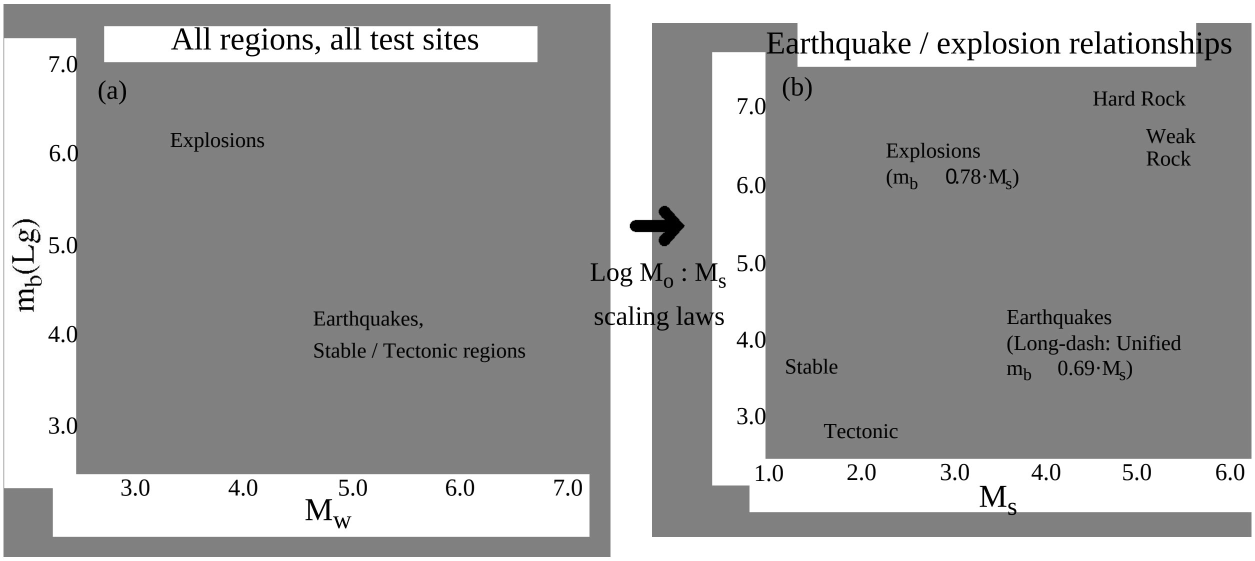

Figure 1. mb(Lg) scaling relationships for earthquakes and explosions. (a) Explosion data are compilations for NTS, KTS, and Novaya Zemlya. One relationship fits all explosion data. Earthquake data are divided into stable (ENA) and tectonic (WUS + CA) regions. Above M_w 4.2, a "unified" relationship (dash line) satisfies data from all regions. (b) Log M_o:M_s scaling laws were used to derive M_s:m_b(Lg) scaling relationships

M_s:m_b(Lg) relationships were obtained from 1st-order scaling models by the use of log M_o:M_s scaling laws for earthquakes and explosions. The global scaling law of Ekstrom and Dziewonski (1988) was used for continental earthquakes. For nuclear explosions, two relationships between isotropic M_o and M_s were drawn upon: one is based on surface wave observations for NTS (Stevens and McLaughlin, 1997), where media is characterized by low velocities, low strength and tectonic release in the form of strike-slip faulting; the other is based on surface wave observations for KTS (Ekstrom and Richards, 1994; Sykes and Cifuentes, 1984), where hard rocks (granites) prevail and tectonic release is typically reverse dip-slip faulting.

The results of applying log M_o:M_s scaling laws are shown in Figure 1b. There are two M_s:m_b(Lg) relationships for explosions: the "weak rock" case is based on NTS experience and plots ~ 0.4 magnitude units (mu) closer to earthquakes. Both relationships scale as $0.78 \cdot M_s$, while earthquake relationships scale as 0.64, 0.75, and 0.69 for stable, tectonic, and unified models, respectively. Convergence of explosion and earthquake populations at small magnitudes is most pronounced for stable continental regions, while the populations are nearly parallel for tectonic regimes. M_s:m_b(Lg) relationships are separated by 1.0 - 1.25 mu for M_s greater than ~3.0, and converge to ~0.8 mu or less at M_s 2.0 depending on tectonic region and geologic/tectonic nature of the test site. A research goal in the near future is to experimentally confirm these M_s:m_b(Lg) relationships for key monitoring regions. Some results should be available by the time of the symposium.

Having established transportability of m_b(Lg) for continental regions, I investigate ways in which the results presented above could be used to quantify both size and regional variations of m_b(P) bias for monitoring regions. I present results based on <u>two methods</u>: (1) extension of Nuttli's test site method to earthquakes using direct comparison of m_b(P) and m_b(Lg) for events with both measurements, and (2) a new approach comparing M_s:m_b(P) observations with M_s:m_b(Lg) relationships developed above. Summarizing the results from (1), I find that the average difference, E[m_b(P) − m_b(Lg)], for ENA (New Madrid seismic zone only), WUS (California and Basin and Range areas only), and CA is −0.06 ± .03, −0.33 ± .03, and −0.12 ± .04 mu, respectively, where uncertainty is one standard deviation (1·σ) and m_b(P) values were taken from EDR or ISC bulletins. Ideally, the difference should be zero for the New Madrid seismic zone since Nuttli's calibration was originally performed for this region. It is not different from zero at the 95% confidence level (2·σ). Results for California and the Basin and Range are consistent with previous bias estimates for western U. S. (Chung and Bernreuter, 1981) and with Nuttli's estimate of test site bias for NTS (Nuttli, 1986a; −0.31 ± .02 mu). While the bias estimate for Tien Shan and neighboring regions of CA is smaller than WUS, I find significant variations when the region is sub-divided: e.g., 15 earthquakes located in eastern Tarim Basin, close to the Lop Nor test site, yield E[m_b(P) − m_b(Lg)] of −0.37 ± .05 mu while observations for earthquakes in or near the Tien Shan mountains show large scatter and average values not significantly different from zero.

The results of a new approach, which can be used to survey m_b bias for large areas, are summarized in Figure 2.

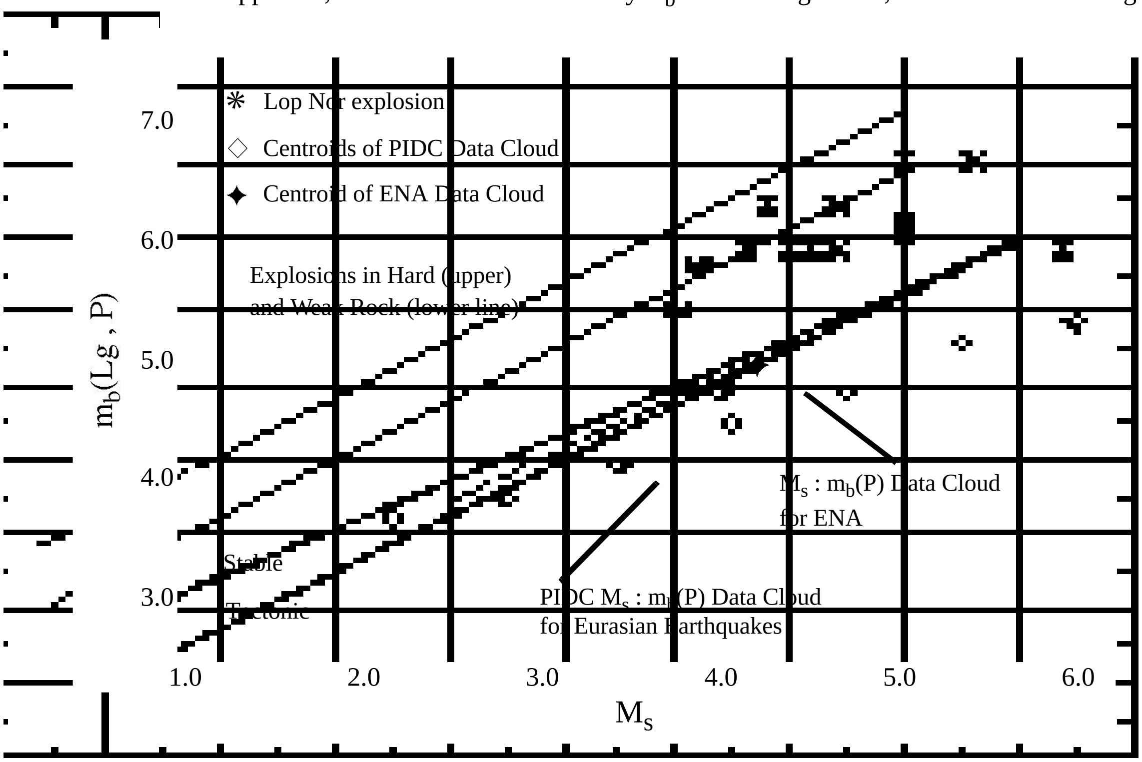

Figure 2. Comparisons of M_s:m_b(Lg) relationships with selected datasets of earthquake and explosion

This figure shows M_s:m_b(Lg) relationships for earthquakes and explosions developed above and several datasets of M_s:m_b(P) observations from published catalogs. Data published by the Prototype International Data Center (PIDC) in Reviewed Event Bulletins (REBs) are shown as dark-gray data cloud representing the distribution of ~800 M_s:m_b

observations for Eurasian events in a ~33 month reporting period. A vast majority of these events are located in tectonic regions of southern Asia. Open diamonds are centroid $m_b(P)$ values obtained by binning M_s data in intervals of 0.5 mu. The smaller, light-gray data cloud is the distribution of 26 M_s:$m_b(P)$ data points for a much smaller dataset of earthquakes located in ENA with $3.8 < M_s < 4.7$. This range was selected because it avoids problems with m_b saturation for larger events and the effects of data censoring on m_b estimates for smaller events. The solid diamond is the centroid of the ENA data cloud.

In this paper I assert that m_b differences between M_s:$m_b(P)$ observations and the unified M_s:$m_b(Lg)$ relationship for earthquakes in the M_s 3.8 - 4.7 range are mainly caused by regional $m_b(P)$ bias. Residuals with respect to the unified relationship were computed for all 26 M_s:$m_b(P)$ observations in the ENA dataset. The mean residual is −0.11 ± .06 mu which is equivalent to the difference in m_b units between the centroid of the ENA data cloud and the unified relationship drawn as a long-dashed line in Figure 2. This result compares favorably with the results from method (1) above; the mean of 52 [$m_b(P) - m_b(Lg)$] observations for earthquakes located throughout ENA is −0.07 ± .03 mu.

In the case of the Eurasian data cloud, comparison of the centroid plotted at M_s 4.2 with the unified M_s:$m_b(Lg)$ relationship suggests that $m_b(P)$ bias is significantly larger for tectonic regions of southern Asia. The m_b difference is about −0.4 mu, six times larger than the difference for ENA. Keeping in mind evidence for spatial variations of [$m_b(P) - m_b(Lg)$] observations in CA discussed above, significant lateral variations in m_b differences are expected across southern Asia, and one of the objectives of this work is to map spatial variations. Preliminary maps will be presented at the symposium.

Turning to M_s:$m_b(P)$ observations for Lop Nor explosions in Figure 2, I applied method (2) once again to make an estimate of $m_b(P)$ bias for the test site. For this application, the question of which M_s:$m_b(Lg)$ relationship to use must be addressed. The source medium at Lop Nor is generally characterized by granite, similar to the former Soviet test site at KTS. On the other hand, studies of tectonic release for Lop Nor explosions (Gao, 1993) find that the mode of tectonic release is strike-slip, which is more the style of large NTS explosions. Thus, log M_o:M_s scaling laws for Lop Nor may represent something of a hybrid between NTS and KTS scaling, and I assumed an M_s:$m_b(Lg)$ relationship with the same slope but midway between the weak and hard rock models in Figure 2. Computing residuals for all data points except the largest explosion (M_s 5.7, which is a significant outlier and plots well above the range of applicability of the models) and taking the mean, the result is −0.35 ± .06 mu. This estimate of the test site bias for Lop Nor agrees very well with direct observations of [$m_b(P) - m_b(Lg)$] for earthquakes located in eastern Tarim Basin close to the test site (see results for method (1) above).

CONCLUSIONS AND RECOMMENDATIONS

The importance of $m_b(Lg)$ transportability for treaty monitoring cannot be over-stated. The results of studies that exploit transportability may well lead to improved understanding of discrimination at small magnitudes and to better monitoring capabilities. Among the results of this study are: (1) unified (or global) M_w:m_b(Lg) scaling relationships for continental earthquakes and nuclear explosions; (2) M_s:m_b(Lg) scaling models for discrimination at small magnitudes; and (3) development of methods for estimating both size and regional variations of m_b(P) bias. Future work will focus on further test and application of these results for successful extension of M_s:m_b technologies to regional data.

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