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**Analysis of m_b - M_s Relationships for Stable and Tectonic Test Sites:
Implications for Source Discrimination and Yield Estimation of North Korean Tests**

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Abstract. m_b - M_s observations for three North Korean tests are consistent with the predictions for a tectonic test site with good coupling and minimal effects of source medium damage. This result suggests that the difficulty with m_b - M_s discrimination for these tests is caused by a combination of (1) little reduction in M_s from Rayleigh-wave interference between damage and explosion sources and (2) significant reduction of m_b due to an upper-mantle test site bias. It did not help that the tests were of moderate to small yields where earthquake and explosion populations tend to merge. This interpretation of discrimination performance brings yield-versus-depth of burial trade-off curves based on m_b and M_s into good agreement, when otherwise the discrepancy between the trade-off curves is unacceptably large for all depths of burial.

I. Introduction.

Following the definitions of Murphy (1996; hereafter referred to as M96) for stable and tectonic test sites with good coupling, predictions of m_b - M_s relationships, including the effects of source medium damage, are presented in this report. The moment tensor model of Patton and Taylor (2008; 2011; hereafter referred to as PT08 and PT11, respectively) introduces damage with the addition of a vertical dipole force system (M_{zz}). This force system can be decomposed into volumetric and deviatoric source components. The deviatoric component is a compensated linear vector dipole (CLVD) with vertical axis of symmetry. The volumetric component is related to dilation (or contraction) of the surrounding source medium. Thus the model predicts two sources of volumetric moment, one direct (cavity formation) and one indirect due to damage processes. Furthermore, it allows for source asymmetries on the horizontal plane, equivalent to vertical strike-slip (VSS) faulting, which might arise as a result of damage and/or tectonic release.

The model predictions will be compared to m_b - M_s observations at tectonic (Nevada Test Site or NNSS) and stable (Semipalatinsk or STS) test sites. The good performance of the model to predict the observations provides confidence with which to interpret the observations for North Korean (DPRK) explosions. The interpretation given to DPRK m_b - M_s observations is in turn used to make inferences about the yield-versus-depth of burial (W -DOB) trade-off curves (TOCs) based on m_b and M_s . It will be shown that this interpretation resolves discrepancies between TOCs that otherwise lead to unacceptably large differences in yield for all DOBs.

II. Effects of Damage on M_s and m_b .

The effect of seismic radiation due to damage on M_s was investigated by PT08. At long periods, it was shown that a CLVD with vertical axis in extension generates Rayleigh waves with opposite polarity of their counterparts radiated by the explosion monopole. This fact means that Rayleigh waves from the two sources destructively interfere on all azimuths, reducing the amplitude of waves radiated by the explosion, and consequently lowering M_s to make explosions look more explosion-like on a plot of m_b versus M_s (presuming damage does not affect m_b , which is discussed below). The perturbation due to damage was estimated by PT08 in their Figure 1b and will be called ΔM_s herein.

It turns out that ΔM_s was computed with respect to the amplitude level of an explosion with apparent moment M_I . PT11 showed that M_I represents the combined volumetric moment from direct effects due to cavity formation and indirect effects, e.g. dilation of the surrounding source medium due to bulking and shear dilatancy or contraction of the medium due to compaction. Patton (2012; hereafter referred to as P12) found a simple relationship between M_I and the theoretical moment M_t due to cavity formation

$$M_I = M_t \cdot \left(\frac{K+2}{3} \right). \quad (1)$$

K is a damage index defined by PT11, where $K = 1$ means no permanent deformation due to damage. $K > 1$ means net dilation of the damaged source medium (and a CLVD with a vertical axis in extension), while $K < 1$ means a net contraction of the damaged medium (and a CLVD with vertical axis in compression).

Because the volumetric part of the source with $K > 1$ radiates larger Rayleigh waves than a pure explosion ($K = 1$) does, the net perturbation with respect to M_s for a pure explosion, which is denoted $\Delta M'_s$, is less than ΔM_s . The equation relating the two is

$$\Delta M'_s(K) = \Delta M_s(K) + \log \left[\frac{K+2}{3} \right]. \quad (2)$$

Figure 1 is a plot of $\Delta M'_s$ along with M_s perturbations computed by PT08. In the next section, $\Delta M'_s$ will be used to compute predictions of m_b - M_s relations for explosions with damage.

Figure 1. M_s perturbations due to damage (solid lines) and to vertical strike-slip (VSS) faulting (dash line). The red line is for $\Delta M'_s$ in equation (2). The result for VSS is predicated on complete and uniform sampling of the source radiation pattern.

$\Delta M_s(F)$ is due to a vertical strike-slip (VSS) source where F is a strength index of this source. For $F < 1$, this perturbation is negligible compared to those caused by damage. This is true for the vast majority of nuclear explosions conducted at NNSS and STS. It is important to note however that, unlike damage, the perturbation due to VSS is dependent on station azimuth, and the result plotted in Figure 1 assumes a network of stations that samples the source radiation pattern thoroughly. If the sampling is biased, then the perturbation can be significantly positive or negative even for $F < 1$.

The question whether or not damage radiation affects teleseismic m_b is a subject of current research (e.g., Taylor and Patton, 2013). At this stage, it is apparent that the degree to which damage affects m_b (~ 1 Hz) and higher frequencies depends critically on the characteristic time τ of the damage process. All but the shortest τ value (0.1 s) gave minimal perturbations Δm_b ; nevertheless, a τ of 0.1 can explain why the yield scaling exponent is 0.75 for explosions of nominal containment depth with damage and not 1.0 or greater as predicted from the effects of pP (Stevens and Day, 1985; Taylor and Patton, 2013). Until our understanding of how damage might contribute to frequencies > 1 Hz improves, I assumed that Δm_b is not a function of K . A yield exponent of 0.75 is heavily supported by observations (M96).

III. m_b - M_s Model Predictions.

Murphy (1996; M96) defines a test site located in a stable region with good coupling, herein referred to as Stable test site, as one with an STS hard rock m_b -yield (W) relation of the form

$$m_b = 4.45 + 0.75 \cdot \log[W] . \quad (3)$$

Likewise, the definition for a site located in a tectonic region with good coupling, referred to as Tectonic test site, is one obtained by subtracting 0.4 magnitude units (mu), which is the m_b bias between NNSS and STS, from equation (3),

$$m_b = 4.05 + 0.75 \cdot \log[W] . \quad (4)$$

Both m_b - W formulas have a yield exponent of 0.75, and this value will be used for m_b - M_s model predictions and for computing W -DOB TOCs later in this report.

Patton (2012; P12) showed that in the absence of damage, the yield exponent of M_s for a pure explosion with cube-root containment practice and uniform coupling is 0.8, e.g.

$$M_s = C + 0.8 \cdot \log[W] \quad . \quad (5)$$

The intercept C was obtained using Pahute Mesa explosions with announced yields.

Seven are located below the water table at near-nominal scaled DOBs. It is desirable to use explosions Benham, Boxcar, Greeley, and Halfbeak with the greatest DOBs to ensure full coupling. The two deepest and largest explosions suffered damage resulting in net compaction ($K = 0.7$ for Boxcar), while Greeley is reported to have a large F value (1.6; Toksöz and Kehrner, 1972). Halfbeak, with a DOB of 819 m, W of 365 kT, and M_s of 5.2 (see P12), gives 3.15 for C ($5.2 - 0.8 \cdot \log[365]$). I adopted a value of 3.2, and reduced it by 0.3 mu to account for a baseline difference between Jih and Baumstark (1994) M_s and AWE M_s (e.g., Blacknest, Atomic Weapons Establishment; Selby *et al.*, 2012; see P12). Throughout this report I will use AWE reported m_b and M_s values whenever possible or AWE-equivalents (e.g., baseline-corrected).

Using equations (3) and (4) and the M_s - W relation so determined above, the following are m_b - M_s relationships for Stable and Tectonic test sites,

$$M_s = 1.07 \cdot m_b - 1.85 \quad (6)$$

and

$$M_s = 1.07 \cdot m_b - 1.4 \quad , \quad (7)$$

respectively, for pure explosions with good coupling and no damage. A justification for using the same M_s - W relation for both sites is provided by the theoretical sensitivities of

long-period Rayleigh wave amplitude A^R to material properties: density ρ , P-wave speed α , Poisson ratio ν , and porosity. It can be shown that A^R is insensitive to these properties because the effect on seismic moment ($\propto \xi^{-0.58} \cdot \rho^{0.21} \cdot \alpha^{0.85}$) increases the amplitude between NNSS and STS, while the elastic Green's function ($\propto \xi^{0.65} \cdot \alpha^{-0.7}$) decreases it.

Note $\xi = \xi(\nu) = (\beta/\alpha)^2$, where β is S-wave speed. The net effect on A^R

$$A^R \propto \xi^{0.07} \cdot \rho^{0.21} \cdot \alpha^{0.15} \quad (8)$$

is small even though material properties are very different at the two test sites.

Figure 2 is a plot of the m_b - M_s relations for Stable and Tectonic test sites. These relations include the effect of damage using the results for $\Delta M'_s$. When compared to the IDC Experimental screening line (Fisk *et al.* 2002), it can be seen that the effect of damage is expected to improve discrimination performance, and of course, a test site m_b bias degrades it.

Figure 2. m_b - M_s relationships for Stable and Tectonic test sites after the definitions of Murphy (1996). The effect of damage on M_s is to lower the relations moving them away from the IDC Experimental screening line (Fisk *et al.*, 2002) shown by the heavy black line. Thus the contribution of damage to the seismic wave field aids discrimination on a plot of m_b versus M_s .

IV. m_b - M_s Models and Observations for Stable and Tectonic Test Sites.

In this section, I compare m_b - M_s observations for Stable and Tectonic test sites with the predictions in Figure 2, as well as predictions for other K values. For NNSS, there are estimates of K values for many Pahute and Rainier Mesa explosions and a sprinkling of Yucca Flats explosions from moment tensor inversions (Patton, 1991). Maximum K values for these explosions = ~ 2.5 . Using a physical basis method for transporting M_s between test sites, P12 finds that the effects of damage are significantly greater for tests conducted at the Balapan test site. Hence K values for the Stable test site should be larger. The comparisons made in this section support these findings.

Figure 3 shows m_b - M_s observations with the predictions for Tectonic and Stable test sites in plots (a) and (b), respectively. The observations for NNSS are the same as those plotted in Figure 4 of PT08. They exhibit a tendency to approach the prediction for $K = 1$ at large yields. This is due to the fact that K decreases from a maximum of 2.5 for small m_b (yields) to 1 or less for the largest shots on Pahute Mesa. On the other hand, a notable difference between the results in this plot and those in Figure 4 of PT08 is seen for $m_b < \sim 5.8$: the model goes through the data in Figure 4, while the model for a K of 2.5 lies above the observations in Figure 3a. Recall that $\Delta M'_s$ is smaller than ΔM_s ; thus the model used by PT08 over-estimated the effect of damage. This is corrected in Figure 3a, because $\Delta M'_s$ is computed with respect to a pure explosion. Now the issue is the discrepancy with the observations, which lie below the model predictions even though the inversion results gave K values in the range between 1.5 and 2.5. As will be discussed

in the Discussion and Conclusion section, the cause of this discrepancy is variations of differential coupling between P and Rayleigh waves with DOB.

Figure 3. Predicted m_b - M_s relationships and observations. (a) NNSS explosions located on Rainier and Pahute Mesas and a few on Yucca Flats are plotted with m_b - M_s relationships predicted for a Tectonic test site. (b) Balapan explosions are plotted with m_b - M_s relationships for a Stable test site.

Comparisons for the Stable test site are made in Figure 3b. The models are for K values of 1, 2.5, 3.0, and 3.5. They bracket the observations of Soviet explosions conducted at the Balapan site. These observations show more scatter than those for NNSS, and there is no evidence for any dependence on m_b (or yield). Both features, along with significantly higher K values, are consistent with a greater role of damage affecting the seismic measurements of magnitude. Patton (2008) discusses why, in the context of material properties, K values do not show dependence on yield for hard rock explosions like they do at NNSS. As discussed above, larger K values were anticipated. In all likelihood, damage is more important at Balapan due to better energy coupling of up-going shock waves and stronger free-surface interactions. The coupling is better because the water table is very shallow.

V. m_b - M_s Models and DPRK Observations.

Figure 4 shows a comparison of the three DPRK explosions to date with models for Stable and Tectonic test sites. m_b and M_s values are reported by AWE Blacknest. The values for the most recent 2013 test should be regarded as preliminary (Selby, pers. comm. 2013). The only two model predictions plotted are for pure explosions ($K = 1$). There is no question that the observations agree much better with the prediction for a Tectonic test site. My interpretation of this finding is straightforward: the difficulty with m_b - M_s discrimination for these tests is caused by a combination of (1) little reduction in M_s from Rayleigh-wave interference between damage and explosion sources and (2) significant reduction of m_b due to an upper-mantle test site bias. It does not help that the explosions were of moderate to small yields where earthquake and explosion populations

tend to merge (Stevens and Day, 1985), as reflected by the trend of the IDC Experimental screening line.

Figure 4. Predicted m_b - M_s relationships for pure explosions at Stable and Tectonic test sites and observations for three DPRK tests to date.

VI. Implications for DPRK W -DOB TOCs.

The general formula for W -DOB trade-off curves (TOCs) is

$$W = \left[10^{(a \cdot M - b)} \cdot h^c \right]^{1/d}, \quad (9)$$

where h is DOB, M is seismic magnitude, $a = 1.0$ for m_b or M_s and $=1.5$ for M_w , b involves the intercept on M - W relations and adjustments to the intercept for material properties, c is the depth scaling of cavity volume V_c , and d is the yield scaling which is mainly controlled by V_c scaling. For M_w , d is identically equal 1.0, while in general d is not equal to 1 for m_b or M_s . This formula presumes that M scales with the low frequency level of the source spectrum, which seems to hold true for many source models for a broad range of yields.

Small adjustments were made to the intercepts of m_b - W and M_s - W relations for material properties in order to equilibrate to those values conjectured to be appropriate for the North Korean test site at Punggye-ri (e.g., 2500 kg/m³, 5100 m/s, and ~0.24 for ρ , α , and ν ; Koper *et al.*, 2008). The size of these adjustments was less than 0.05 mu for both magnitudes. V_c - W scaling has unity exponent (Denny and Johnson, 1991), and the depth scaling exponent $c = 0.63$ based on the results of Rougier *et al.* (2010). Without test site bias, $b = 5.75$ and $d = 0.96$; the m_b for 2013 is 5.0. With test site bias, $b = 5.35$. For the TOC based on M_s , $b = 4.26$, $d = 1.01$, and $M_s = 3.9$. The resulting three TOCs are plotted in Figure 5.

Figure 5. Yield versus depth of burial trade-off curves (W -DOB TOCs) for the 2013 DPRK test. Two are based on m_b , the blue line using Murphy's m_b - W relation for Stable test sites as the basis and the red line using the m_b - W relation for Tectonic test sites with a 0.4 m_b bias correction. The green line is the TOC based on M_s . The black dash line is the critical scaled DOB (SDOB) for the effects of shear damage to be noticeable at the free surface of an intact granite medium with flat surface topography based on hydrodynamic modeling calculations of Rougier *et al.* (2010). Thus, points on TOCs lying to the left of the black line would show damage on the free surface while points lying to the right would not.

The m_b TOC without a bias correction differs from the M_s TOC by almost a factor of 3 over the entire range of burial depths. This much difference is unacceptably large. With the bias correction of 0.4 mu, the agreement between TOCs is much improved. The m_b TOC is only 20% larger on average than the M_s TOC.

It should be noted that the M_s TOC may be under-estimated because there is evidence that K is somewhat greater than 1 for the 2013 test, lying in the range, $1.2 < K < 1.8$. (Note: K values for tests conducted in 2006 and 2009 are believed to be very close 1 for reasons discussed in PT08 and PT11.) Inferences about K for the 2013 test will be the subject of a future paper. If K does lie in the above-stated range, Figure 1 implies that a positive ~ 0.1 mu correction should be applied to the measured M_s in order to equilibrate to a pure explosion source. This implies a $10^{0.08}$ increase in yield or 20%, which would bring the M_s TOC into excellent agreement with the m_b TOC with a bias correction.

VII. Discussion and Conclusion.

Effects of differential coupling on Tectonic m_b - M_s relations. I noted the discrepancy between model predictions and NNSS m_b - M_s observations in Figure 3a. Because K values from moment tensor inversions of Pahute and Rainier Mesa explosions rarely exceed 2.5, this discrepancy needs to be explained. P12 discusses coupling differences between P and Rayleigh waves for “Mesa” explosions and reasons for coupling variations with depth to be stronger for Rayleigh waves than for P waves. The coupling of P waves weights down-going waves more heavily than the coupling of Rayleigh waves, which require a free surface for their existence. Down-going waves encounter water-saturated media with

good coupling while surface waves sample the integrated effects of rays leaving at all takeoff angles, including up-going rays that go through dry, porous media.

Figure 6 (top) shows coupling models for P and Rayleigh waves. Variation with depth is represented by a sigmoid function (see equation 14 of PT11). The model for P waves was derived in P12 (see p. 1380); the shallow depth asymptote is constrained to be -0.5μ based on the findings of M96. I modified the Rayleigh model in Figure 9 of PT11 because the data on which it was based (Taylor, 1982) included Yucca Flats explosions detonated in alluvium and unconsolidated tuffs, making the depth dependence too strong for Mesa explosions. The M_s scaling results reported in P12 suggests that a better estimate can be found by taking a log average of the P wave model and the Rayleigh wave model in PT11. The new model is plotted in Figure 6.

Figure 6. (top) Models of P- and Rayleigh-wave coupling variations with depth for Pahute and Rainier Mesa explosions and (bottom) coupling corrections accounting for m_b - M_s scaling differences based on these models. These corrections are to be applied to the m_b - M_s relationships for the Tectonic test site in Figure 3a.

The lower graph represents the differential coupling in magnitude units (μ) between P and Rayleigh waves. This result is an indication of how much the models in Figure 3a should be adjusted to account for coupling differences. For example, many explosions with $m_b < 5$ were detonated on Rainier Mesa with DOBs on the order of 400 m or less. The differential coupling curve would say to lower the model predictions by $\sim 0.4 \mu$. This will bring the predictions into good agreement with the observations. The cluster of explosions near m_b 5.5 are mainly those on Pahute Mesa with DOBs between 550 and 650 m. The model adjustment based on differential coupling is $\sim 0.2 \mu$, again bringing the adjusted model predictions into better agreement with the observations.

m_b TOCs versus M_s TOC. In my opinion, the question of magnitude bias under the North Korean test site at Punggye-ri adds sizable uncertainty to the estimates of m_b TOC that nullifies their usual preference over TOCs based on M_s . Indeed, I have much higher confidence in the M_s TOC than I do in either m_b TOC plotted in Figure 5. There is evidence on both sides of the bias issue.

1. The strongest case against a bias may be the recent study by Ichinose *et al.* (2012). Nevertheless, this work does not dispel the evidence found from global t^* studies (Hwang *et al.*, 2011) and Q tomography studies (Lawrence and Wyss, 2006) for significant attenuation associated with the tectonic regions bordering the “Pacific Ring of Fire” and the so-called “China Anomaly” of low Q and shear wave speeds.
2. Stead *et al.* (2007) estimated m_b bias for areas of southeastern Asia using two methods: (1) comparisons between M_w from coda waves and m_b , and (2)

- determinations of station bias for three stations near North Korea. They find systematic variations along the Korean Peninsula, with m_b bias tending to decrease from south to north. Under the southern Korean Peninsula, the bias appears to be less than 0.3-0.4 mu, but they conclude that further work is needed to improve the stability and resolution of their preliminary results.
3. A well-calibrated $m_b(\text{Lg})$ scale can be helpful for assessments of upper-mantle bias. Zhao *et al.* (2013) reported $m_b(\text{Lg})$ estimates for all three DPRK tests in good agreement with teleseismic m_b . These results suggest little or no bias. On the other hand, Chun *et al.* (2011) estimated $m_b(\text{Lg})$ for 2006 and 2009 tests 0.3-0.4 mu larger than those estimated by Zhao *et al.* The reason for the difference is related to their respective Q models. Zhao *et al.*'s model gives relatively high Lg Q and is based on earthquake data on long travel paths while Chun *et al.*'s model used data for earthquakes and the 2006 DPRK test collected on short paths for stations located closer to the Punggye-ri test site and yielded much lower Lg Qs. These paths are more representative of Lg propagation characteristics from explosions at near-region distances because the energy tends to get trapped in the upper regions of the crust (Baker *et al.*, 2004; Priestley and Patton, 1997).
 4. Murphy *et al.* (2011) find that a high Q model like one for STS fits the overall shape of the network-averaged P-wave spectrum for the 2009 test better than a Q model for NNSS. However, the observed spectrum has limited bandwidth, and the fall off to high frequencies is not well resolve. Also their use of a Mueller-Murphy spectrum apparently never considered the effect of burial depth and the

degree to which Q models could tradeoff with source spectra over a limited bandwidth of frequencies.

It's clear that the issue of a test site m_b bias is an open question for North Korea based on these few studies which for the most part are limited in scope or specificity to the Punggye-ri test site. The question of bias between NNSS and STS took years to be resolved in the 80s and 90s, and required comprehensive and focused studies. It was not confirmed until the Joint Verification Experiment (JVE) was conducted at STS. We may never have the opportunity to do an experiment in North Korea; so careful consideration is needed to plan the next round of studies involving remote observations to improve upon what has been learnt to date.

In defense of M_s TOCs, it is important to note that there is nothing extraordinarily anomalous about the M_s for any of the DPRK tests in the view of models proposed by PT08 and PT11. Murphy *et al.* (2011) argues that M_s is anomalous because of the unacceptably large yield estimates they obtain compared to their m_b estimates. Murphy and Bennett (2013) reported 63 kT for the 2013 test and allude to tectonic release (Murphy *et al.*, 2011) as a biasing factor in the yield estimate. I would argue that tectonic release has nothing to do with biasing M_s for these tests, and that the problem with high yield estimates is caused by an erroneous M_s - W relationship.

The model of Murphy *et al.* (2011) involves an extensional tectonic regime where the maximum compressive stress is vertical, and minimum compressive stresses are virtually equal in the two horizontal principal-axes directions. In terms of a body-force system, the

manifestation of this tectonic release model is a CLVD with a vertical axis of symmetry, and it predicts constructive interference of Rayleigh waves with the explosion monopole on all azimuths. Consequently, M_s should be biased high relative to the M_s - W relation of Stevens and Murphy (2001), which it is, and the yield estimates are too large.

Figure 7 compares M_s - W observations for Soviet Peaceful Nuclear Explosions (PNEs) with the relation of Stevens and Murphy. The yields are provided in Sultanov *et al.* (1999), and M_s values are taken from Selby *et al.* (2012). Virtually all of the PNEs plot above this relation. Are we to conclude that a tensile tectonic regime like that purported for North Korea is also responsible for large M_s for all of these PNEs? In light of extensive studies of tectonic stress of continental interiors (e.g., Zoback *et al.*, 1989) showing that maximum compressive stresses are typically horizontal, this is a preposterous conclusion.

Figure 7. M_s - W observations for Peaceful Nuclear Explosions conducted by the Soviet Union throughout the interior of the Eurasia landmass and M_s - W relationships. The solid line is the relation used by Murphy *et al.* (2010) to estimate yield and is based on the study of Stevens and Murphy (2001). The dash line is the relation obtained in section III using well-coupled Pahute Mesa explosions after accounting for the effects of damage.

Stevens and Murphy's M_s - W relation is motivated by empiricism and can only be regarded as an apparent relationship. On the other hand, the M_s - W scaling coefficient from P12 and the relation found in section III of this report has a physical basis. Its scaling coefficient and intercept have accounted for the effects of damage. Furthermore, it is based on explosions with good coupling and nominal scaled DOB ($\sim 120 \text{ m/kt}^{1/3}$). Thus, PNE observations lie below this relation because many such explosions were over-buried, and the effects of damage could have reduced M_s for some explosions to some degree.

In conclusion, I have presented predictions of m_b - M_s relationships, including the effects of source medium damage based on the source model of Patton and Taylor (2008; 2011) for Stable and Tectonic test sites following definitions of Murphy (1996) for such sites. DPRK observations for all three tests agree much better with the prediction for a Tectonic test site than they do for a Stable site. My interpretation of this fact is straightforward: the difficulty with m_b - M_s discrimination for these tests is caused by a combination of (1) little reduction in M_s from Rayleigh-wave interference between damage and explosion sources and (2) significant reduction of m_b due to an upper-mantle test site bias. The fact that these explosions were of moderate to small yields where earthquake and explosion populations tend to merge did not help matters. This interpretation was carried over to the calculation of yield-versus-depth of burial trade-off curves. Such curves based show good agreement if an m_b bias appropriate for Tectonic test sites is applied, when otherwise a yield discrepancy for the two magnitudes is unacceptably large for all depths of burial.

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