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Reply

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We thank Karl Veith for his thoughtful comments and welcome the opportunity to respond to it and provide some additional information and considerations which did not make it into the paper because of lack of space.

Veith suspects two problems with our approach. The first is that the source/station distribution is not representative for shallow earthquakes. The second is that the use of station/source corrections might have reduced the scatter in the data.

We give the source/station distribution, as well as an event depth histogram in Figure 1. By its very nature, this is representative for deep (> 100 km) events and GSN stations, and the data set lacks sources in regions which have shallow seismicity only. However, stations and sources are interchangeable because of the principle of reciprocity. One might still object that events deeper than, say, 220 km traverse the asthenosphere only once, whereas shallow events would be twice affected. The body wave amplitude is a function of both the geometrical spreading and of the attenuation. If the two cannot be separated with the available data, our corrections would miss this effect and shallow event corrections would indeed be biased. We note that our shallowest event is at 116 km depth, and there are 5 events with $h < 150$ km, providing raypaths that traverse the asthenosphere twice or almost so. In fact, the gradient in our corrections Q_b between 100 and 200 km depth is a clear indication of the sensitivity of our data to asthenospheric attenuation. For $\Delta > 60°$, the correction changes about 0.2 between 100 and 200 km, giving an attenuation factor of 0.63, corresponding to a quality factor ≈ 90 for a 1 Hz ray of 120 km length, which is low but still of the right order of magnitude for the asthenosphere. Extrapolating this to the surface is a rough way of accounting for similar transmission losses due to attenuation, scattering, and crustal reflections. Even if the error in that is 50%, Q_b would be in error by only 0.1, small in comparison to the observational scatter.

Obviously, we could not have reduced scatter by the introduction of source corrections without losing all information on the depth dependence of Q_b and Q_w. Although we did not discuss this in our paper, we did check for systematic station bias by calculating station Q_b and Q_w averages for $40° < \Delta < 80°$. Since many GSN stations did not enter the data set until the end of the period we considered (1996), possibilities to do so reliably are limited. For only 26 stations we could average over at least 8 values. For 17 of these the bias in Q_b so estimated was 0.2 or less, with one extreme bias of -0.44 for OBN; only 7 stations had a bias in Q_w larger than 0.1 (SBC extreme 0.21). These are relatively small values, largely explainable as uncertainties in the estimates rather than as reliable offsets in averages. Most importantly, we found that biases Q_b and Q_w for the same station do not correlate (correlation coefficient 0.06, giving a probability of zero correlation of 75%). This sheds doubt on a common station-based mechanism for amplitude offsets and we decided not to attempt to correct for such. Rather, we think the stability of our Q_w observations attest to the reliability of GSN instrumentation and the adequacy of GSN station siting for amplitude measurements.

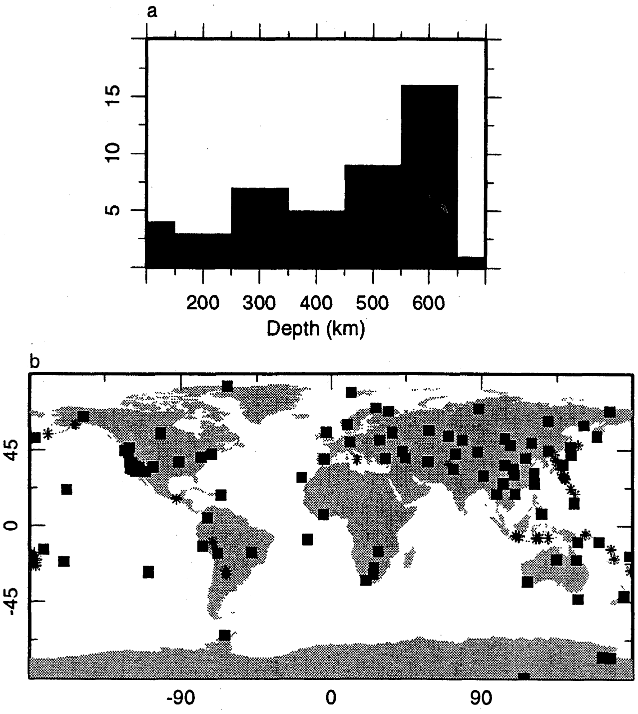

Figure 1. [a] Histogram of the depths of earthquakes used by *Nolet et al.,* [1998], [b] locations of GSN stations (filled squares) and earthquake epicenters (stars).

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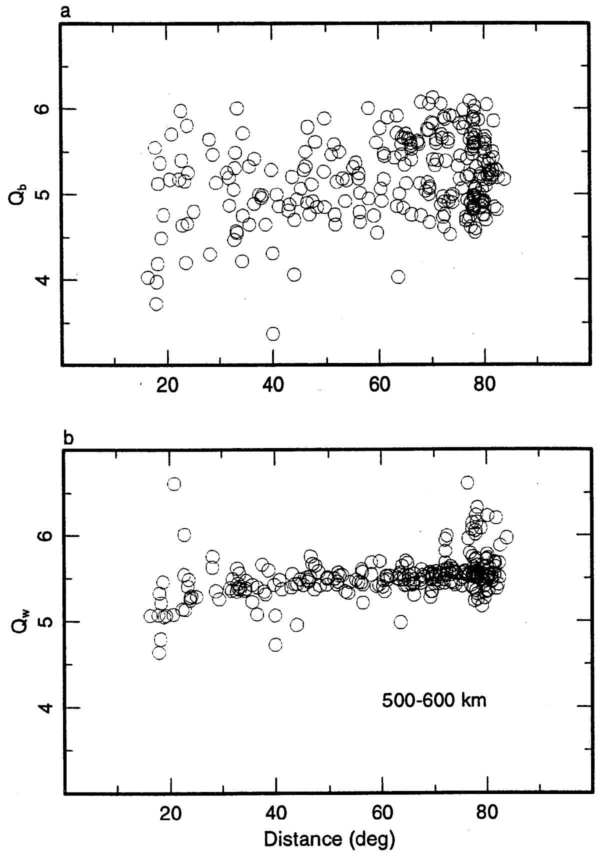

Figure 2. [a] Observed scatter in individual correction factors Q_b established for events in the 500-600 km depth range. [b] idem, for Q_w.

The most important question raised by Veith is what causes the scatter, and it is also the most difficult to answer with any certainty. In Figure 2 we show the scatter for all events in the 500-600 km depth range. This selection gives a better idea of the true scatter than the figures in our original paper because the latter included both scatter *and* variations due to source depth. For Q_b, the average absolute deviation from a simple line fit is 0.38, which reflects amplitude variations by a factor of 2.4; in contrast, Q_w has an average deviation of 0.13, reflecting variations by only ±35%. This is an important difference, and any mechanism to explain the observed scatter will have to explain this behaviour. Whereas Q_b is measured for peak periods of 1-4 s, those for Q_w reflect a dominant period close to the full length of the wavetrain.

Variations in the attenuation by the asthenosphere are frequency dependent. One passage through the asthenosphere will typically reduce the amplitude of a 2 s P pulse by some 20-25% but that of a 15 s pulse by less than 5%. This is insufficient to explain the scatter in both Q_b and Q_w or the absence of strong correlation in station bias by variations in attenuation, e.g. in arc regions.

Errors in the Harvard scalar moment estimates would give errors common to both Q_b and Q_w, through the calibration with *Giardini's* [1988] equation. In view of the small scatter observed for Q_w this fails to explain the large scatter in Q_b.

The influence of lateral heterogeneity is difficult to quantify in the absence of adequate computational tools. Whereas the moment magnitude M_w will be mainly affected by focusing effects, m_b is very sensitive to changes in the P waveform, caused by multipathing of high frequency energy or complexities of the rupture process, Such scatter was avoided by *Veith and Clawson* [1972], who used nuclear sources. This is certainly preferable for establishing corrections for surface sources. Unfortunately, it gives no direct information on the depth dependence, and even a shallow event study using nuclear tests would be impossible to repeat with GSN stations in view of the Comprehensive Test Ban Treaty.

We conclude that the scatter of ± 0.4 magnitude unit found for Q_b does not reflect a shortcoming in the analysis used by us, but reflects problems inherent to the definition of m_b. We stand by our conviction that very detailed correction charts for m_b are not warranted in view of these problems. Seismologists continue to use m_b, even though it is clear (also from our study) that M_w provides a much more stable measurement, valid for a larger range of magnitudes. The argument is usually that one needs to keep the seismicity catalogues homogeneous. Perhaps we need to reverse the argument and make a serious effort to translate historical m_b into M_w, and only work with M_w from now on. The rapid transformation to digital arrays makes this soon possible, but it will require the development of correction factors Q_w valid for particular regions. We think our study has certainly established reliable Q_w for use at teleseismic distances, and hope it will be followed by similar regional studies.

References

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