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7.7 Double-couple radiation and m_b residuals

Introduction

Since the double-couple force was established to model shear fractures, observed amplitudes have been used in different ways to determine fault plane solutions of earthquakes. In particular, amplitude ratios between P- and S-phases and the radiation pattern of surface waves are often applied for this purpose. P-phase amplitudes observed at different stations have also been used to estimate the parameters of the source mechanism. Particularly for long-period data observed amplitudes correlate well with the theoretically estimated radiation pattern. Consequently, amplitudes or amplitude ratios of long-period body waves are useful to estimate the double-couple radiation pattern.

On the other hand, the body-wave magnitude m_b, the most commonly used estimate of the size of an earthquake, is calculated from short-period P-type phases. The observed amplitudes show a large scatter which is the result of several effects like source complexity, lateral heterogeneities in the source region and along the ray path, different transfer functions of the crust below the stations, uncertainties in the station characteristics, non unified measuring procedures, and amplitude variations due to the double-couple radiation of the source.

The m_b-values and their corresponding station residuals are usually estimated under the assumption that the influence of the double-couple radiation is averaged out when amplitude observations are available from different azimuths. The contribution of the double-couple radiation to the observed magnitude residuals is the topic for investigation in this study.

Data

To study the influence of the double-couple radiation for m_b one needs a large set of events with known radiation pattern, and for the same suite of events one also needs a set of observed amplitudes. Such data are now available. Since January 1995 the GSETT-3 International Data Center (IDC) provides amplitudes and periods of all phases automatically analyzed with a common algorithm. Additionally, the seismological group of the Harvard University publishes for all larger events (m_b about 5.0 or larger) Centroid Moment Tensor (CMT) solutions with the best fitting double-couple mechanism for these events. By comparing these two data sources 728 common events in the first nine month of 1995 were found. For these events, all available m_b-observations were retrieved from the IDC data base. All observations from stations with poor data quality or uncertain instrument response were excluded, but altogether 9728 amplitude observations could be used.

To reduce the influence of several changes in the IDC software during the first year of the GSETT-3 experiment, the source parameters were taken from the CMT-solutions. It is especially important to obtain reliably estimated depth values. After reestimating the epicentral distance and correcting all amplitude measurements using the Veith-Clawson (1972) attenuation values, 9728 new station magnitudes, 728 new m_b-values, and 9728 new magnitude residuals were calculated. Fig. 7.7.1 shows the absolute value of all residuals as a function of the new m_b-values.

Influence of the double-couple radiation on m_b

The rule applied to automatically measure amplitudes at the IDC is to use the maximum amplitude within the first 5 seconds after the arrival time. Therefore all phases at each station theoretically arriving in the first 5 seconds after the first P-type onset were calculated using the IASPEI91 tables (Kennett and Engdahl, 1991). For these phases the relative amplitude radiation from the double-couple source was calculated (e.g. Aki and Richards, 1980) using azimuth and ray parameter of the onset. For surface-reflected phases (pP or sP), the relative radiation was multiplied by the corresponding surface reflection coefficient for plane waves (e.g. Müller, 1985). To model the effect of smaller ray-path perturbations these relative radiation factors were calculated for many radiation angles around the theoretical value (i.e. ± 5 deg azimuth, ± 5 deg dip angle for direct P-onsets, ± 15 deg dip for surface reflections, and ± 15 deg for the incidence angle at the surface) and then a mean relative radiation value was calculated for all onsets. Finally, the phase with the maximum radiation was taken to represent the relative double-couple radiation for each event-station combination. With this procedure the phase which theoretically contributes the most to the observed amplitude was used, but it was not possible to model the interference effects between the different onsets arriving within the first 5 seconds of the signal.

Fig. 7.7.2 shows all observed m_b-residuals as a function of the relative double-couple radiation and a straight line calculated with a least-squares fit. The observed residuals show, beside all scatter, a small but clearly visible dependency on the relative double-couple radiation.

Observed station magnitudes can now be corrected for this effect and new m_b-values can be calculated. Because the recalculated m_b-values were also a function of the double-couple radiation, several iterations were necessary to reduce the double-couple effect. Finally the following magnitude-correction formula for the double-couple radiation was found:

$$m_b\,(dc) = \log\,(A/T) + q + a1 * dc + a2$$

with:

A - measured amplitude [nm]

T - dominant period [s]

q - Veith-Clawson attenuation value

dc - relative double-couple radiation

$a1 = 0.39609 \pm 0.12085$

$a2 = -0.19925 \pm 0.09210$

Fig. 7.7.3 shows the station residuals after applying the correction formula for the double-couple radiation. The corrected mean absolute station residuals and the standard deviation are about 2% smaller than without the correction (0.31675 ± 0.41726 instead of 0.32356 ± 0.42519). This can also be seen in Fig. 7.7.4, where all corrected absolute magnitude residuals are plotted versus the corrected m_b-values. These corrected m_b-values are up to

0.2 magnitude units different from the uncorrected ones. Fig. 7.7.5 shows the change in the m_b-values due to double-couple compensation plotted as a function of the uncorrected m_b-values. No specific magnitude-dependent trend can be seen in the data.

Testing the results with NEIC-data

The estimated relation between double-couple radiation and magnitude residuals was also tested on another independent data set. For 3639 events between 1 March 1990 and 31 December 1994, published Harvard CMT-solutions were used to correct the corresponding 212,696 reported amplitude observations in the EDRs of the NEIC. A similar technique as described for the IDC-data was applied. All distances were taken from the EDRs and, as far as available, an estimated instead of a fixed value was taken as depth of the events, either from the EDRs or from the CMT-solutions. As done by the NEIC, the uncorrected m_b-values were recalculated with the Gutenberg-Richter (1956) attenuation values. To see the effect of the radiation pattern, the new magnitudes and residuals were calculated for *all* reported amplitudes for which b-values from the Gutenberg-Richter tables were available. This is somehwat different from the NEIC procedure which uses a 25% trimmed mean.

In contrast to the IDC-data the EDRs contain a large number of relatively shallow events for which also sP contributes to the maximum amplitude in the first 5 seconds. Because of the high reflection coefficient of sP at the Earth's surface, the relative amplitude radiation of sP can become larger than 1. This range of relative radiation was not modeled with the IDC-data and therefore the formula developed could not fit the NEIC data equally well. But with the following quadratic relation, for which the linear part is similar to the values in the formula for the EIDC-data, the double-couple radiation could be described as:

$$m_b\,(dc) = \log(A/T) + b + a1*dc*dc + a2*dc + a3$$

where

A - measured amplitude [nm]

T - dominant period [s]

b - Gutenberg-Richter attenuation value

dc - relative double-couple radiation

$a1 = -0.12447 \pm 0.05584$

$a2 = 0.43326 \pm 0.07288$

$a3 = -0.17193 \pm 0.04672$

Fig. 7.7.6 shows the uncorrected residuals. Although the spread of the data is now much larger than for the GSETT-3 data set, the dependency of the residuals on the double-couple radiation is still visible (note the unequal distribution of the large symbols around the zero line). The size of the symbols corresponds with the number of hits per radiation-residual combination. Fig. 7.7.7 shows the magnitude residuals after correcting the amplitudes with the NEIC correction formula. The larger symbols (more data) between 0 and 1 are now distributed more symmetrically around the zero line. The rare data with a relative double-couple radiation above 3.0 are considered as outlayers and are not modelled. The reduction of the mean absolute residuals and the standard deviation is for this data set about 1.5%, a little bit less than in the case of the IDC-data, but still significant (0.31228 ± 0.41845 instead of 0.31704 ± 0.42344). Another estimation of this relation was done using the Veith-Clawson attenuation curve instead of the Gutenberg-Richter values. The results were very similar and the values for a1, a2, and a3 were within the above estimated standard deviations.

Again the m_b-values estimated with double-couple corrections differ up to about 0.2 magnitude units from the uncorrected values (Fig. 7.7.8), and again no specific magnitude-dependent trend is seen. To test if these corrected m_b-values are better than the uncorrected, both data sets were compared with the corresponding seismic moments M_0 published with the CMT-solutions. Fig. 7.7.9 shows for all 3639 *uncorrected* NEIC events the m_b-values versus M_0. Assuming a linear relation between M_0 and m_b a least squares fit gives:

$$m_b = a1 * M_0 + a2$$

with

$a1 = 0.41507 \pm 0.07445$ $a2 = -4.77852 \pm 0.36850$

and a mean absolute m_b residual of 0.17554 ± 0.22614. The discrepancy for large M_0-values is the result of the known saturation of the m_b-scale for larger events. Fig. 7.7.10 shows for the same events the relation between M_0 and the *corrected* m_b-values. The parameters of the least squares fit are now:

$a1 = 0.42159 \pm 0.07381$ $a2 = -4.95596 \pm 0.36533$

and a mean absolute m_b residual of 0.17268 ± 0.22227. The double-couple corrected m_b-values correlate better with the independently estimated M_0-values as the parameters of the M_0/m_b-relation show smaller standard deviations and the mean m_b residual is 1.7% smaller.

Conclusion

It has been demonstrated that a dependency exists between the double-couple radiation of earthquakes and the observed station magnitudes and consequently the corresponding m_b-values. If fault-plane solutions are available, it is easy to correct for this effect. Normally such solutions are only known for larger events, but whenever individual station m_b-values are needed with a very high accuracy (e.g., to investigate magnitude relations), or when station-magnitude residuals should be estimated, the correction of amplitude observations for the double-couple radiation will reduce the scatter and should be taken into account. Also the NEIC and the ISC could calculate corrected m_b-values for all events with known double-couple radiation and publish them in their bulletins.

On the other hand, this study has shown that the effects of double-couple source radiation on short-period amplitude patterns is much smaller than the variations associated with other factors such as lateral heterogeneities in the earth. This means that when calculating *average* event magnitudes from a well-distributed global network, quite accurate values can be obtained even when the source mechanism is unknown.

Acknowledgement

We thank the Seismological Group of the Harvard University for making all the thousands of CMT-solutions available via the Internet.

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T. Kværna

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Müller, G. (1985): The reflectivity method: a tutorial. *J. Geophys.* 58, 153-174.

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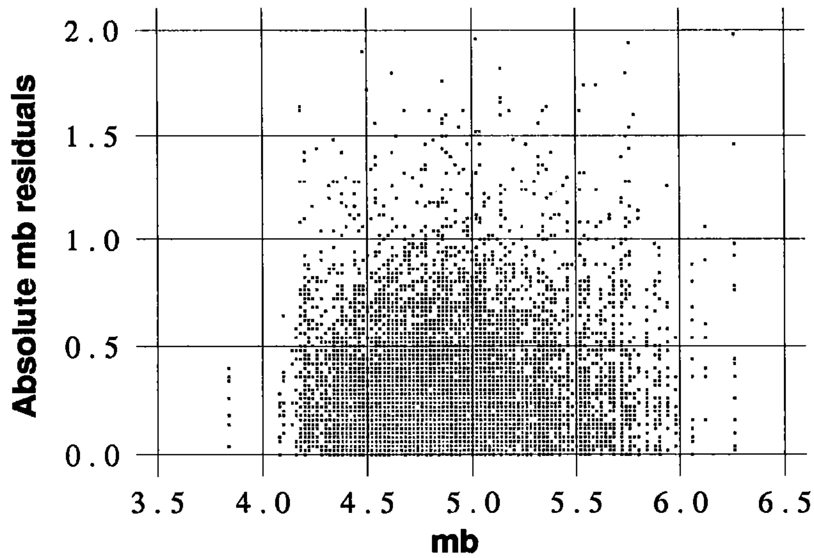

Fig. 7.7.1. Absolute values of station magnitude residuals plotted as a function of event magnitude. The database used in this figure consists of 728 events recorded at the GSETT-3 stations with altogether 9728 phase observations.

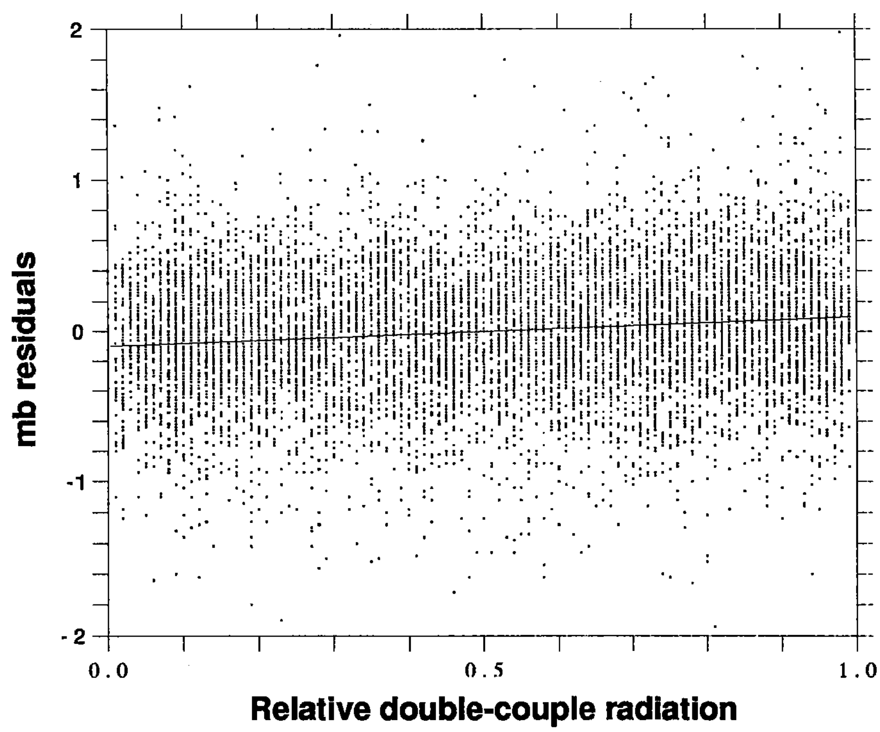

Fig. 7.7.2. Station magnitude residuals plotted a a function of relative double-couple radiation, for the database described in the text. The coefficients of the straight line were calculated by least squares.

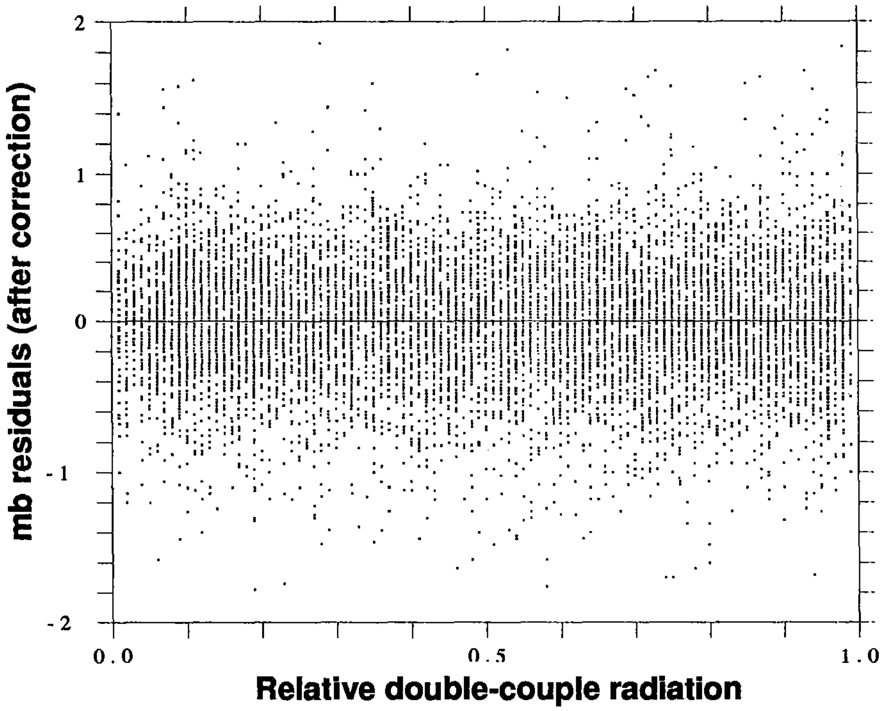

Fig. 7.7.3. Same as in Fig. 7.7.2, but after applying the correction formula for double-couple radiation.

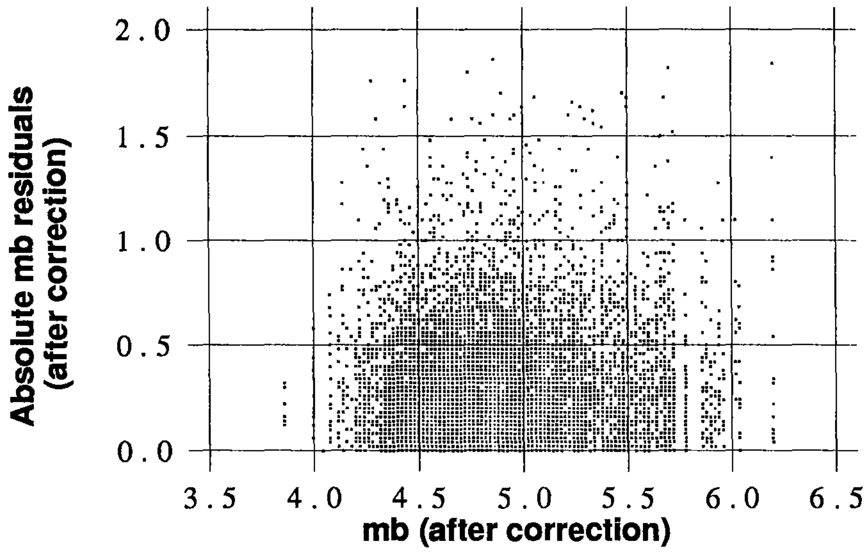

Fig. 7.7.4. Absolute values of station magnitude residuals plotted as a function of event magnitude, both calculated after applying the correction formula for double-couple radiation.

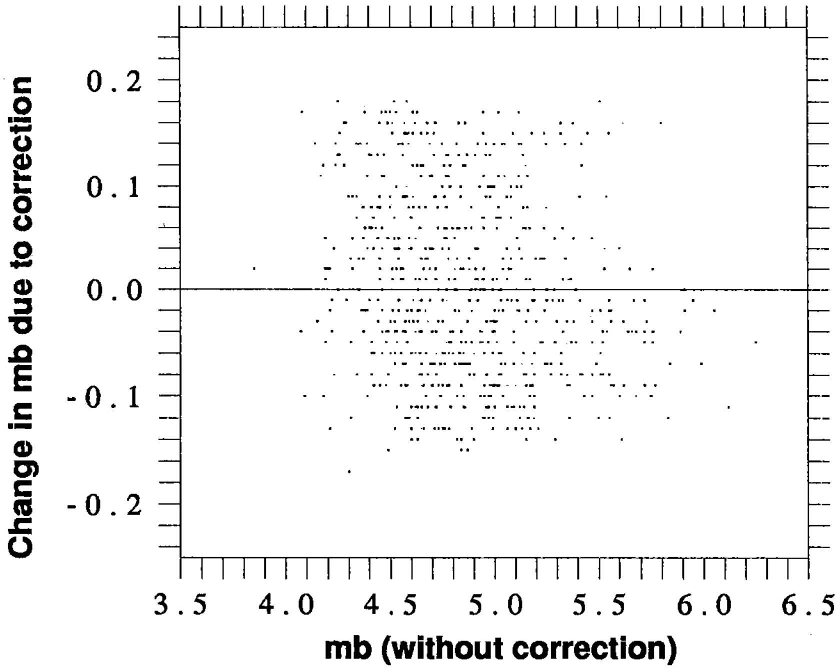

Fig. 7.7.5. Change in event magnitude introduced by applying the correction formula for double-couple radiation, plotted against the uncorrected event magnitude.

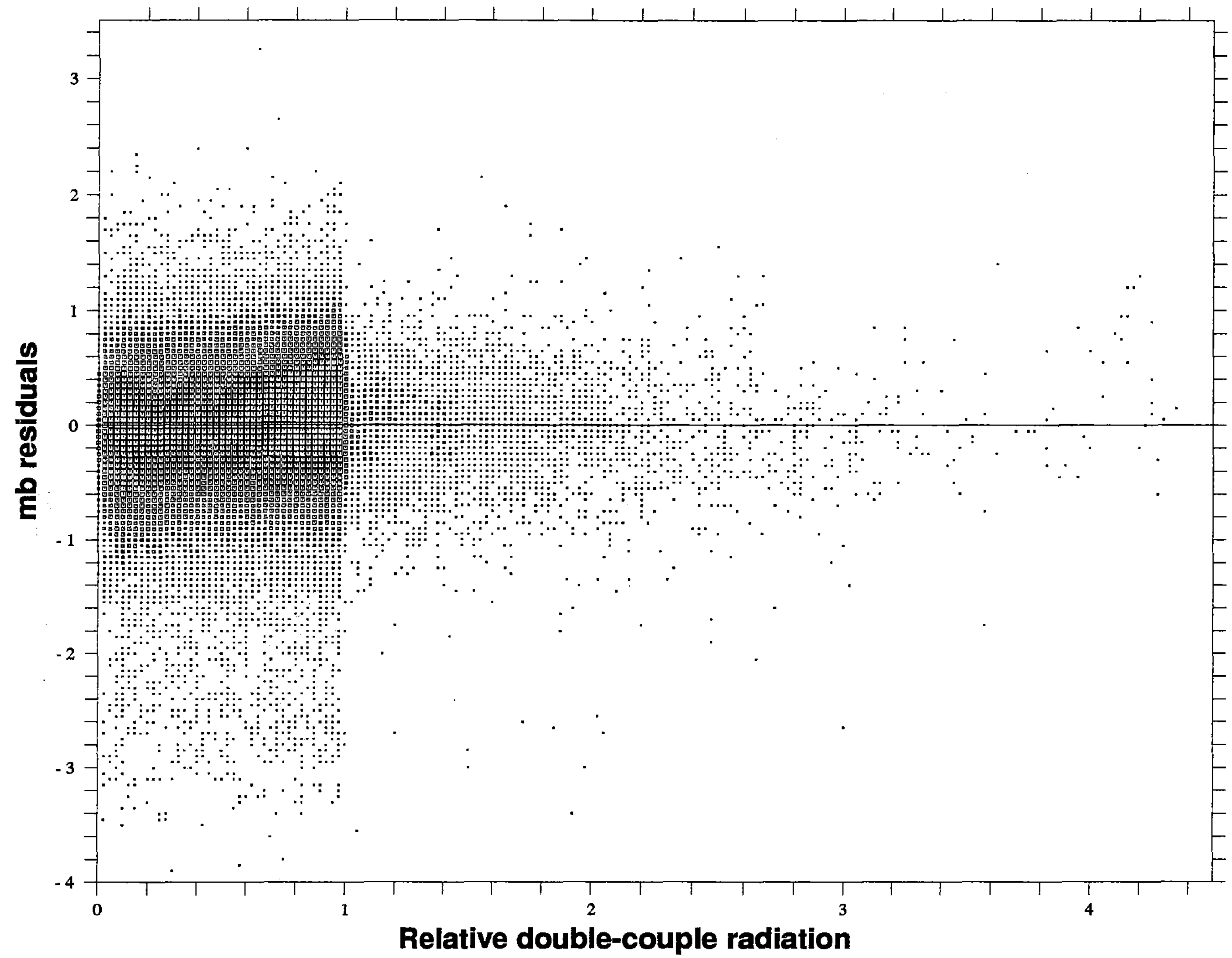

Fig. 7.7.6. Station magnitude residuals plotted as a function of relative double-couple radiation. The database used in this figure consists of 3639 events reported by NEIC with altogether 212696 amplitude observations. The size of the symbols represents the number of hits per radiation-residual combination.

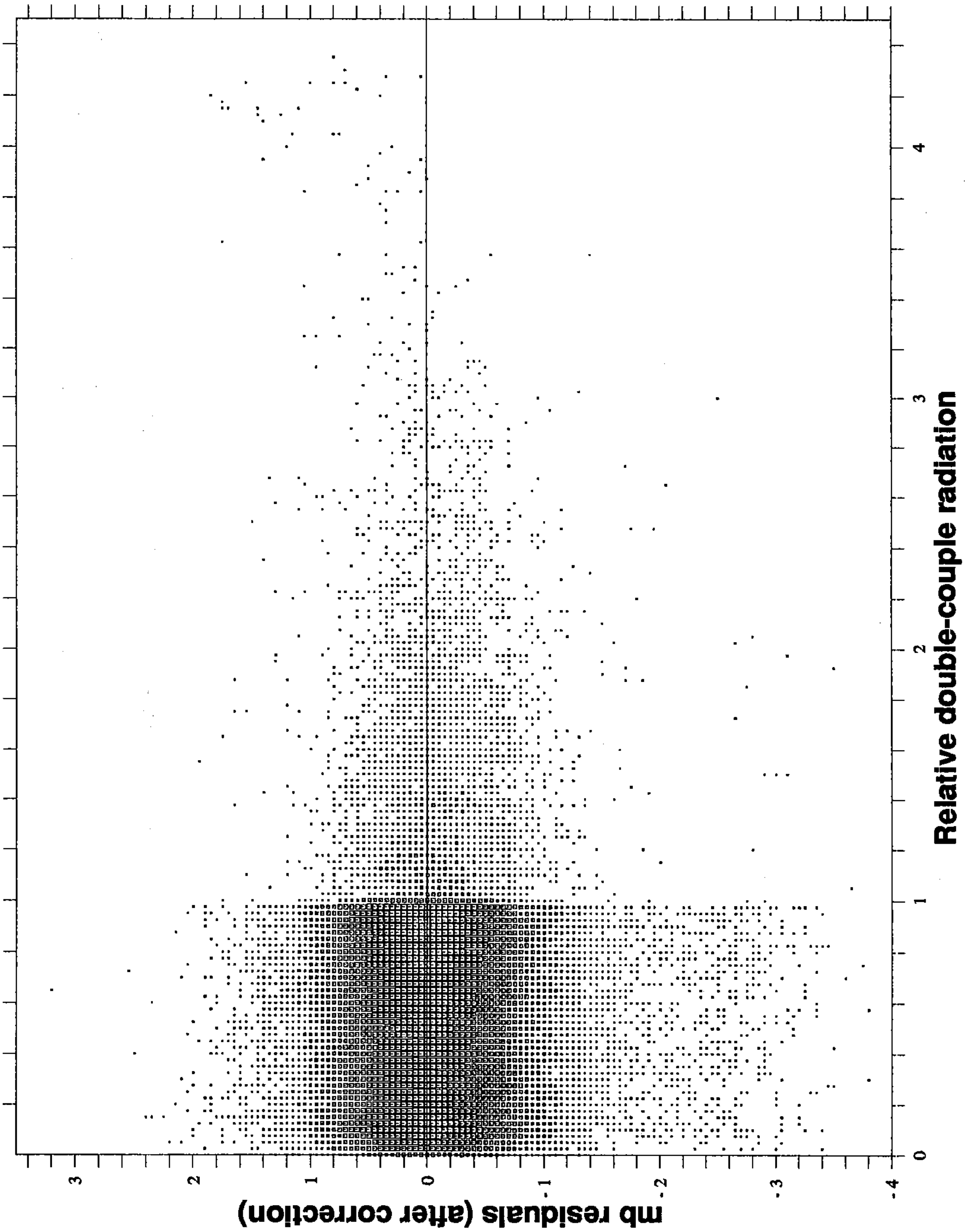

Fig. 7.7.7. Same as in Fig. 7.7.6, but after applying the correction formula for double-couple radiation.

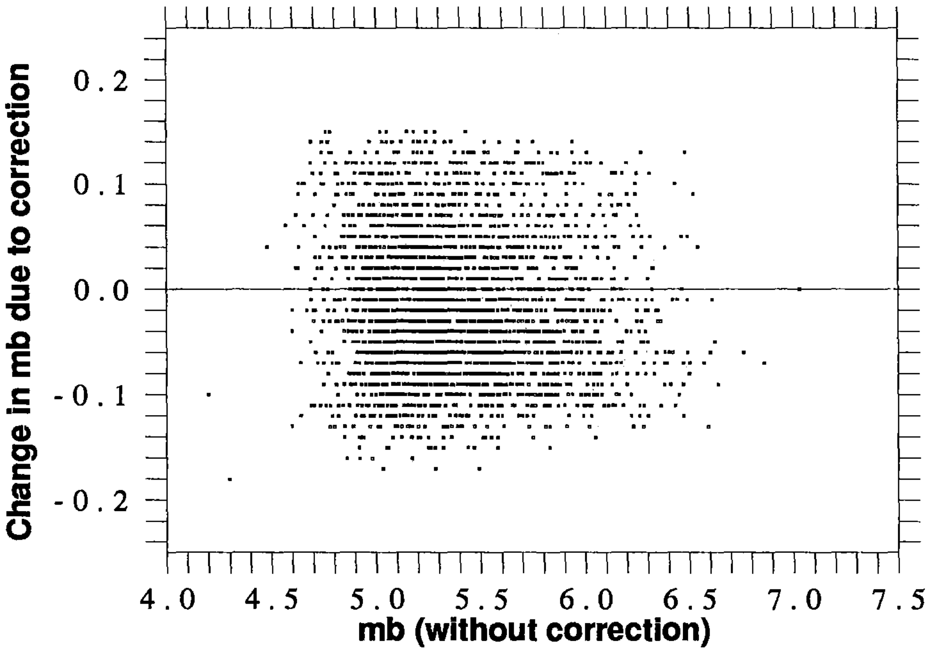

Fig. 7.7.8. Change in event magnitude introduced by applying the correction formula for double-couple radiation, plotted against the uncorrected event magnitude.

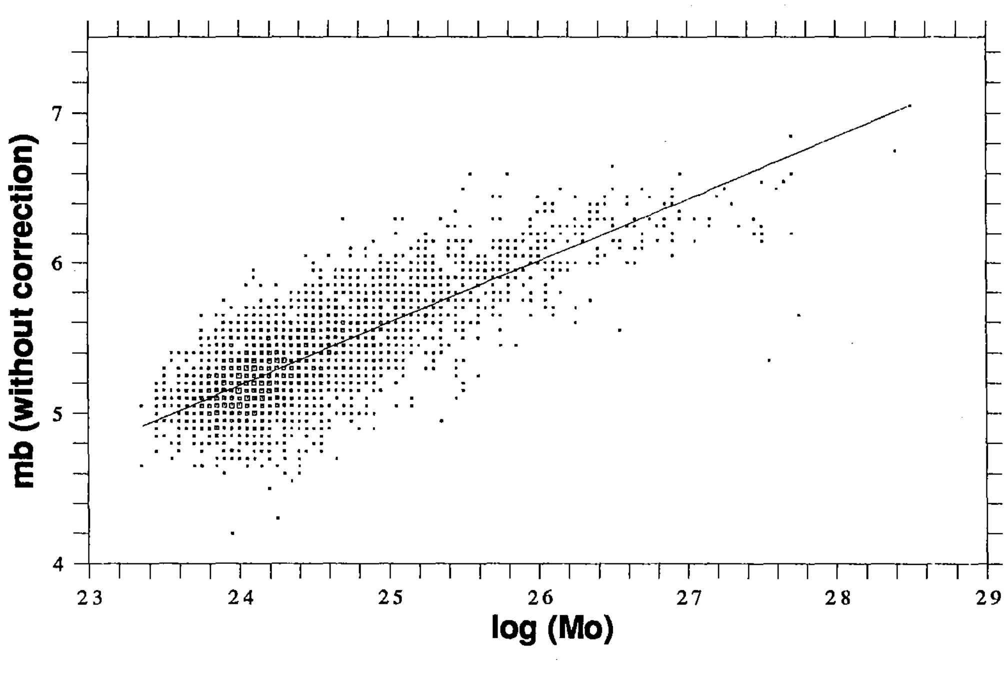

Fig. 7.7.9. Uncorrected event magnitude plotted against the seismic moment of the 3639 NEIC events. The coefficients of the straight line were calculated by least squares.

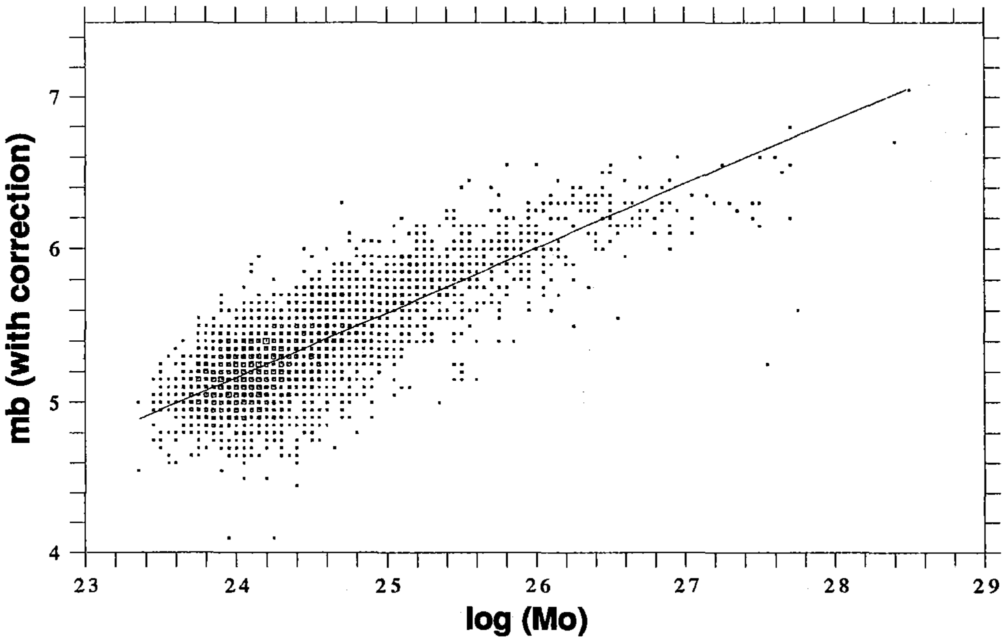

Fig. 7.7.10. Event magnitudes calculated after applying the correction formula for double-couple radiation plotted against the seismic moment of the 3639 NEIC events. The coefficients of the straight line were calculated by least squares.