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7.1 RMS Lg analysis of Novaya Zemlya explosion recordings

Introduction

In recent years, much attention has focused upon the use of the seismic Lg phase to determine the yield of underground nuclear explosions. In the first of a number of Lg studies undertaken by the NORSAR staff during the 1980s, Ringdal (1983) analyzed digital NORSAR Lg data of selected Semipalatinsk events. He found that, when using NORSAR RMS Lg instead of P waves recorded at NORSAR to estimate source size, it was possible to eliminate effectively the magnitude bias relative to worldwide m_b observed at NORSAR between Degelen and Shagan River explosions. The method consisted of averaging log(RMS) values of individual NORSAR channels, filtered in a band of 0.6 to 3.0 Hz in order to enhance Lg signal-to-noise ratio. Ringdal and Hokland (1987) expanded the data base and introduced a noise compensation procedure to improve the reliability of measurement at low SNR values. They were able to identify a distinct P-Lg bias between the Northeast and Southwest portions of the Shagan River Test Site, a feature that was confirmed by Ringdal and Fyen (1988) using Gräfenberg array data. Ringdal and Marshall (1989) combined P- and Lg-based source size estimators to estimate the yields of 96 Shagan River explosions from 1965 to 1988, using data on the cratering explosion of 15 January 1965 as a reference for the yield calculations.

Hansen, Ringdal and Richards (1990) analyzed available data from stations in China and the Soviet Union, and found that RMS Lg of Semipalatinsk explosions measured at these stations showed excellent consistency. They concluded that for explosions at Semipalatinsk with good signal-to-noise ratio, m_b(Lg) may be estimated at single stations with an accuracy (one standard deviation) of about 0.03 magnitude unit. It is noteworthy that this accuracy was consistently obtained for a variety of stations at very different azimuths and distances, even though the basic parameters remained exactly as originally proposed by Ringdal for NORSAR recordings (0.6–3.0 Hz bandpass filter, RMS window length of 2 minutes, centered at a time corresponding to a group velocity of 3.5 km/s).

In this paper we apply Ringdal's method to NORSAR and Gräfenberg recordings of Novaya Zemlya explosions. This initial study focuses on the Northern Novaya Zemlya test site, and we will only consider explosions occurring after 1976.

Data

The data base for this study comprises seismic recordings at NORSAR and Gräfenberg for 18 presumed underground nuclear explosions at Novaya Zemlya from 1976 through 1990.

The NORSAR array (Bungum, Husebye and Ringdal, 1971) was established in 1970, and originally comprised 22 subarrays, deployed over an area of 100 km diameter. Since 1976 the number of operational subarrays has been 7, comprising altogether 42 vertical-component SP sensors (type HS-10). In this paper, analysis has been conducted using data from these 7 subarrays. Sampling rate for the NORSAR SP data is 20 samples per second, and all data are recorded on digital magnetic tape.

The Gräfenberg array (Harjes and Seidl, 1978) was established in 1976, and today comprises 13 broadband seismometer sites, three of which are 3-component systems. The instrument response is flat to velocity from about 20 second period to 5 Hz. Sampling rate is 20 samples per second, and the data are recorded on digital magnetic tape.

Fig. 7.1.1 shows the Lg propagation paths from Novaya Zemlya to the two arrays. The distance and azimuth are 2200 km and 256 degrees to NORSAR, compared to 3300 km and 243 degrees to Gräfenberg. Both paths cross the Barents Sea, and as observed by several authors (see Baumgardt, 1990), this implies significant Lg blockage effects. The result is particularly visible on NORSAR records, which show relatively weak Lg energy compared to the P and Sn phases.

Examples of NORSAR recordings of one of the explosions are shown in Fig. 7.1.2. We note that this (as well as most of the other events analyzed) exhibits signal clipping of both P and Sn. This is a result of the very strong seismic signals recorded at NORSAR for Novaya Zemlya explosions, in combination with the limited dynamic range of the digital recording system. For this reason, we have chosen to measure the RMS Lg at NORSAR by selecting a 2-minute window in the Lg coda, starting at 10 1/2 min after the origin time of the event (see the figure). Previous studies of Semipalatinsk explosions have shown that the RMS method is not very sensitive to the exact positioning of the time window, as long as it is kept the same for all events analyzed.

On Fig. 7.1.2, we have also indicated a two-minute P coda window, which we have used to calculate NORSAR P coda magnitudes for the explosions, using the array RMS method. The P coda window starts 6 minutes after the event origin time.

In Fig. 7.1.3 we show an example of GRF recordings of one of the explosions. Here, the dynamic range is sufficient to avoid any clipping, and we have selected a two-minute window which includes the main Lg energy, starting 16 minutes after event origin time.

Analysis results

Applying the RMS measurement technique using our standard filter band (0.6–3.0 Hz) and averaging over array elements as described by Ringdal and Hokland (1987), we arrive at results listed in Tables 7.1.1 through 7.1.3.

Table 7.1.1 gives our results for NORSAR P-coda magnitudes, using the time window indicated on Fig. 7.1.2. A constant correction factor has been added to the log(RMS) values to make these coda magnitudes consistent, on the average, with world-wide m_b.

Table 7.1.2 covers the NORSAR Lg results, and shows that RMS Lg can be estimated for all the events processed, including two events below $m_b = 5.0$ (events 2 and 4). (For the 27 Sep 78 explosion, no NORSAR data are available.)

Table 7.1.3 gives corresponding Lg results for the Gräfenberg array. Here, the smallest of the events (Event 4) had too low SNR to allow reliable measurements.

The m_b values listed in Tables 7.1.1 through 7.1.3 are taken from Lilwall and Marshall (1986) for events up to 1984, and have been calculated from NEIC station reports for later events.

Fig. 7.1.4 shows a comparison of world-wide m_b and NORSAR P coda magnitudes. We note that the correspondence is excellent (orthogonal standard deviation is only 0.027). Thus the NORSAR recordings appear to provide a very stable measure of m_b for events from this test site.

Figs. 7.1.5 and 7.1.6 are scatter plots comparing world-wide m_b to NORSAR and Gräfenberg RMS Lg magnitudes. We note that there is a considerable scatter in both of these plots. In particular, it appears that the majority of events have almost the same M(Lg), whereas the m_b values vary from below 5.7 to above 6.0 for this group.

It is especially interesting to note that NORSAR M(Lg) deviates significantly from m_b, whereas NORSAR P coda corresponds very closely to m_b.

Fig. 7.1.7 shows a scatter plot of Gräfenberg versus NORSAR M(Lg). The correspondence is excellent, with an orthogonal standard deviation of only 0.035. The scatter is further reduced (to 0.025) if we consider only events with at least 5 available GRF channels (Fig. 7.1.8). Thus, we obtain the same close correspondence between Lg observations from these two arrays for Novaya Zemlya explosions as has previously been observed for Semipalatinsk events.

With the current lack of independently obtained calibration data, it would be premature to draw any firm conclusions as to the relative accuracy of m_b and M(Lg) in estimating yields of these explosions. Nevertheless, it would appear that the close grouping in M(Lg), especially seen for the NORSAR data, is unlikely to be a coincidence. It would seem reasonable to conclude that this group of explosions has very nearly the same yield, in spite of the divergence in m_b estimates. However, additional analysis, in particular including available Lg data from Soviet stations for this event set, should be performed in order to further test this hypothesis.

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Ev	Date	Origin time	mb	NCH	Noise	STD	Pcoda	STD	CORR	m(Pcoda)
01	29/09/76-273:03.00.00.00		5.77	40/42	1.867	0.064	3.133	0.049	3.132	5.732
02	20/10/76-294:08.00.00.00		4.89	40/42	1.933	0.066	2.405	0.048	2.378	4.978
03	01/09/77-244:03.00.00.00		5.71	34/41	1.777	0.062	3.151	0.045	3.150	5.750
04	09/10/77-282:11.00.00.00		4.51	40/41	1.908	0.066	2.139	0.047	2.046	4.646
05	10/08/78-222:08.00.00.00		6.04	33/39	1.862	0.066	3.352	0.046	3.352	5.952
06	27/09/78-270:02.05.00.00		5.68	*00/00	0.000	0.000	0.000	0.000	0.000	0.000
07	24/09/79-267:03.30.00.00		5.80	38/39	1.852	0.059	3.182	0.050	3.182	5.782
08	18/10/79-291:07.10.00.00		5.85	28/39	1.918	0.050	3.222	0.050	3.221	5.821
09	11/10/80-285:07.10.00.00		5.80	32/38	1.911	0.060	3.176	0.041	3.176	5.776
10	01/10/81-274:12.15.00.00		5.91	20/39	1.959	0.063	3.282	0.037	3.282	5.882
11	11/10/82-284:07.15.00.00		5.52	27/40	1.828	0.085	2.952	0.050	2.951	5.551
12	18/08/83-230:16.10.00.00		5.84	25/39	1.776	0.054	3.170	0.054	3.169	5.769
13	25/09/83-268:13.10.00.00		5.71	24/39	2.148	0.055	3.125	0.052	3.123	5.723
14	25/10/84-299:06.30.00.00		5.77	28/41	1.932	0.063	3.144	0.066	3.143	5.743
15	02/08/87-214:02.00.00.00		5.71	28/40	1.908	0.080	3.170	0.048	3.169	5.769
16	07/05/88-128:22.50.00.00		5.52	27/40	1.478	0.066	3.014	0.038	3.014	5.614
17	04/12/88-339:05.20.00.00		5.79	30/40	2.055	0.061	3.223	0.046	3.222	5.822
18	24/10/90-297:14.58.00.00		5.60	38/40	1.822	0.070	3.019	0.044	3.018	5.618

Table 7.1.1. NORSAR RMS P coda magnitudes for events in the data base. The table lists event number, origin date and time, world-wide m_b and a list of measurements made in this study:

NCH	: Number of NORSAR data channels used, and the total number available
Noise	: Array averaged log RMS values in a noise window
STD	: Corresponding standard deviation across array
Pcoda	: Array averaged log RMS values in the P coda window
STD	: Corresponding standard deviation
CORR	: Noise-corrected log RMS values of the P coda
m(Pcoda)	: P coda magnitude derived by adding a constant term to the noise-corrected values.

Ev	Date	Origin time	mb	NCH	Noise	STD	Lg	STD	LgCORR	MLg(NAO)
01	29/09/76-273:03.00.00.00		5.77	40/42	1.867	0.064	3.161	0.065	3.160	5.770
02	20/10/76-294:08.00.00.00		4.89	40/42	1.933	0.066	2.479	0.065	2.461	5.071
03	01/09/77-244:03.00.00.00		5.71	34/41	1.777	0.062	3.147	0.065	3.147	5.757
04	09/10/77-282:11.00.00.00		4.51	40/41	1.906	0.063	2.278	0.059	2.235	4.845
05	10/08/78-222:08.00.00.00		6.04	33/39	1.862	0.066	3.174	0.057	3.173	5.783
06	27/09/78-270:02.05.00.00		5.68	*00/00	0.000	0.000	0.000	0.000	0.000	0.000
07	24/09/79-267:03.30.00.00		5.80	38/39	1.852	0.059	3.170	0.063	3.169	5.779
08	18/10/79-291:07.10.00.00		5.85	28/39	1.918	0.050	3.128	0.060	3.127	5.737
09	11/10/80-285:07.10.00.00		5.80	32/38	1.911	0.060	3.175	0.060	3.174	5.784
10	01/10/81-274:12.15.00.00		5.91	20/39	1.959	0.063	3.173	0.044	3.172	5.782
11	11/10/82-284:07.15.00.00		5.52	27/40	1.828	0.085	2.994	0.074	2.993	5.603
12	18/08/83-230:16.10.00.00		5.84	25/39	1.776	0.054	3.197	0.062	3.197	5.807
13	25/09/83-268:13.10.00.00		5.71	24/39	2.148	0.055	3.189	0.047	3.187	5.797
14	25/10/84-299:06.30.00.00		5.77	28/41	1.932	0.063	3.196	0.075	3.195	5.805
15	02/08/87-214:02.00.00.00		5.71	28/40	1.908	0.080	3.197	0.078	3.196	5.806
16	07/05/88-128:22.50.00.00		5.52	27/40	1.478	0.066	3.109	0.064	3.109	5.719
17	04/12/88-339:05.20.00.00		5.79	30/40	2.055	0.061	3.191	0.053	3.190	5.800
18	24/10/90-297:14.58.00.00		5.60	38/40	1.822	0.070	2.996	0.058	2.995	5.605

NOTE: The M(Lg) values have been obtained by adding a constant correction term (2.610) to the noise corrected log RMS Lg values. This correction term is preliminary, and may be subject to later revision.

Table 7.1.2. NORSAR RMS Lg magnitudes for events in the data base. The structure of the table is analogous to Table 7.1.1. The rightmost column lists the NORSAR M(Lg) values.

Ev	Date	Origin time	mb	NCH	Noise	STD	Lg	STD	LgCORR	MLg(GRF)
01	29/09/76-273:03.00.00.00		5.77	02/04	1.118	0.086	2.025	0.035	2.022	5.799
02	20/10/76-294:08.00.00.00		4.89	03/04	1.318	0.047	1.435	0.041	1.245	5.022
03	01/09/77-244:03.00.00.00		5.71	03/04	1.023	0.007	2.097	0.021	2.095	5.872
04	09/10/77-282:11.00.00.00		4.51	*03/04	1.223	0.008	1.255	0.085	0.000	0.000
05	10/08/78-222:08.00.00.00		6.04	05/13	1.223	0.069	1.988	0.102	1.982	5.759
06	27/09/78-270:02.05.00.00		5.68	06/13	1.270	0.132	1.896	0.114	1.883	5.660
07	24/09/79-267:03.30.00.00		5.80	07/13	1.217	0.097	2.053	0.118	2.048	5.825
08	18/10/79-291:07.10.00.00		5.85	10/13	1.350	0.100	1.905	0.116	1.887	5.664
09	11/10/80-285:07.10.00.00		5.80	13/13	1.350	0.128	1.968	0.115	1.955	5.732
10	01/10/81-274:12.15.00.00		5.91	08/13	1.416	0.069	2.019	0.099	2.006	5.783
11	11/10/82-284:07.15.00.00		5.52	13/13	1.291	0.121	1.828	0.120	1.808	5.585
12	18/08/83-230:16.10.00.00		5.84	12/13	1.214	0.122	2.066	0.135	2.062	5.739
13	25/09/83-268:13.10.00.00		5.71	13/13	1.126	0.103	2.004	0.145	2.000	5.777
14	25/10/84-299:06.30.00.00		5.77	13/13	1.382	0.131	2.069	0.124	2.060	5.837
15	02/08/87-214:02.00.00.00		5.71	12/13	1.033	0.138	2.035	0.147	2.033	5.810
16	07/05/88-128:22.50.00.00		5.52	12/13	1.018	0.162	1.881	0.148	1.877	5.654
17	04/12/88-339:05.20.00.00		5.79	13/13	1.195	0.147	2.038	0.128	2.034	5.811
18	24/10/90-297:14.58.00.00		5.60	08/13	1.452	0.214	1.817	0.150	1.773	5.550

NOTE: The M(Lg) values have been obtained by adding a constant correction term (3.777) to the noise corrected log RMS Lg values. This correction term is preliminary, and may be subject to later revision.

Table 7.1.3. Gräfenberg RMS Lg magnitudes for events in the data base. The structure of the table is analogous to Table 7.1.1. The rightmost column lists the Gräfenberg M(Lg) values.

Lg propagation paths

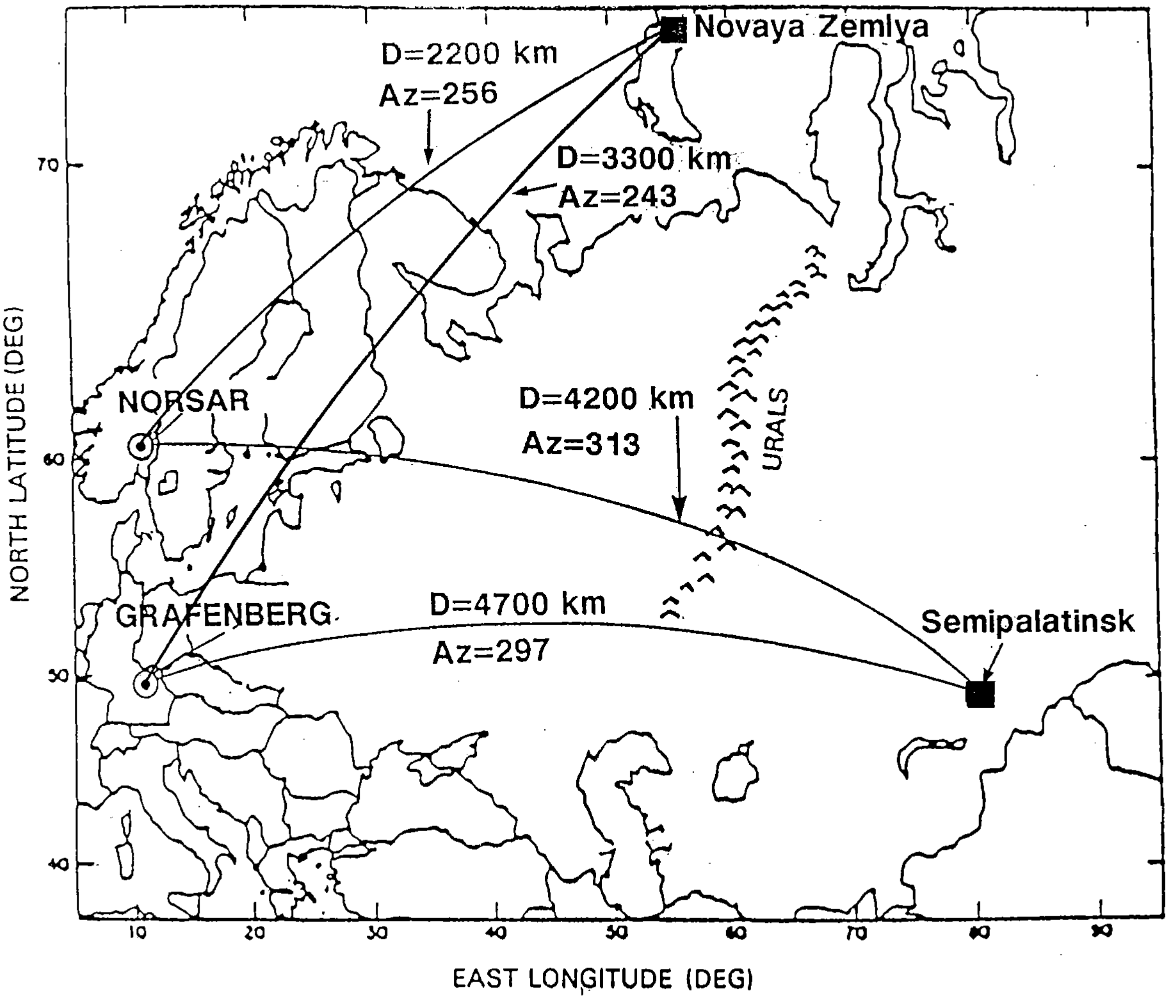

Fig. 7.1.1. Map showing the Lg propagation paths from the main Soviet test sites (Novaya Zemlya and Semipalatinsk) to the NORSAR and Gräfenberg arrays.

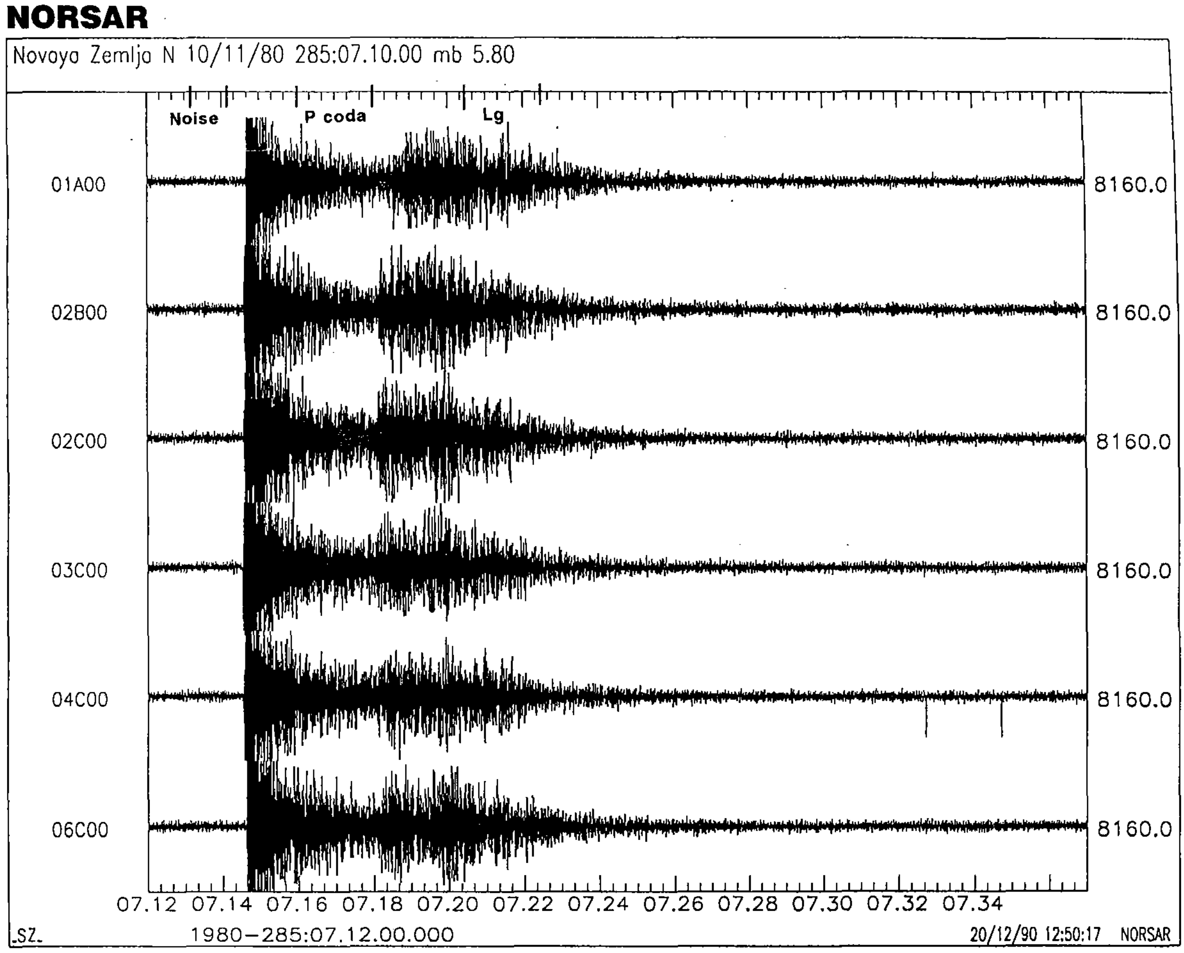

Fig. 7.1.2. Example of NORSAR recordings of a Novaya Zemlya explosion (11 October 1980). The center instrument of each of the 7 subarrays is displayed, covering 25 minutes of unfiltered data. The positioning of time windows used for RMS Lg, Pcoda and noise measurements is indicated. Note the clipping of the initial P and that also the S phase is close to exceeding the dynamic range.

GRAFENBERG

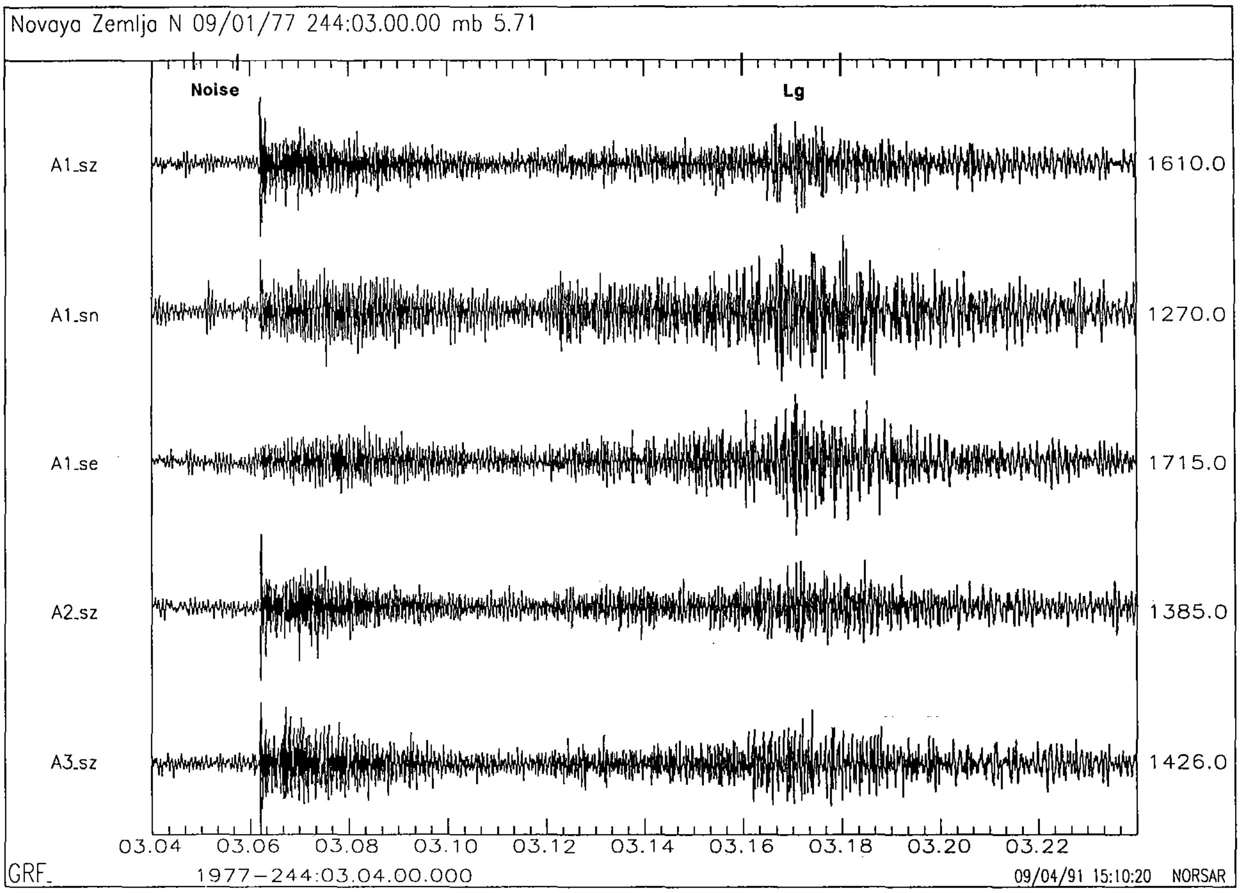

Fig. 7.1.3. Example of Gräfenberg recordings of a Novaya Zemlya explosion (1 September 1977). The figure shows 20 minutes of unfiltered data from the three components of the A1 seismometer site and the vertical-component A2 and A3 instruments. Note that the horizontal components have not been used in our analysis. The positioning of time windows used for RMS Lg and noise measurements is indicated.

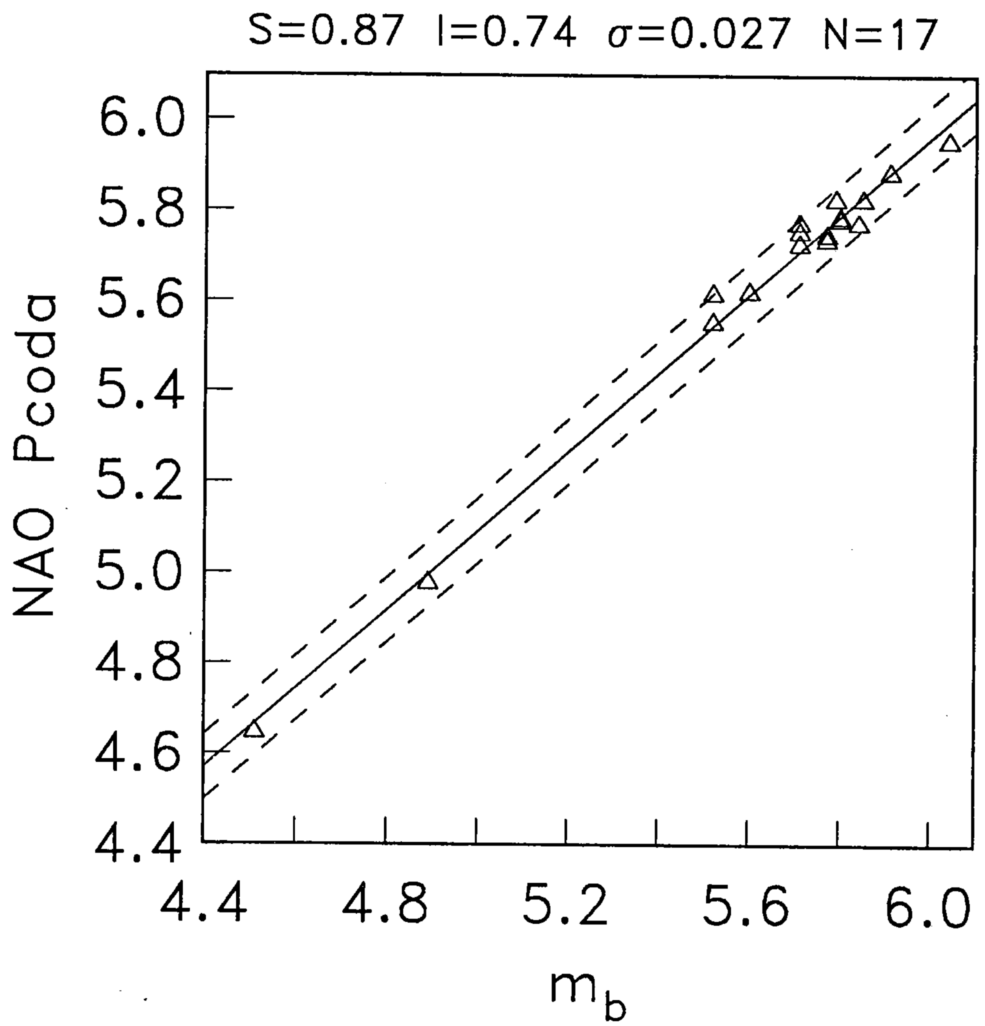

Fig. 7.1.4. Plot of NORSAR RMS P coda m_b versus world-wide m_b for events in the data base. The straight line has been obtained by least-squares regression with respect to the horizontal axis, and the stippled lines correspond to plus/minus two standard deviations. The slope (S), intercept (I), orthogonal standard deviation (σ) and number of data points (N) are listed on the figure. Note the remarkably close correspondence between the two estimators.

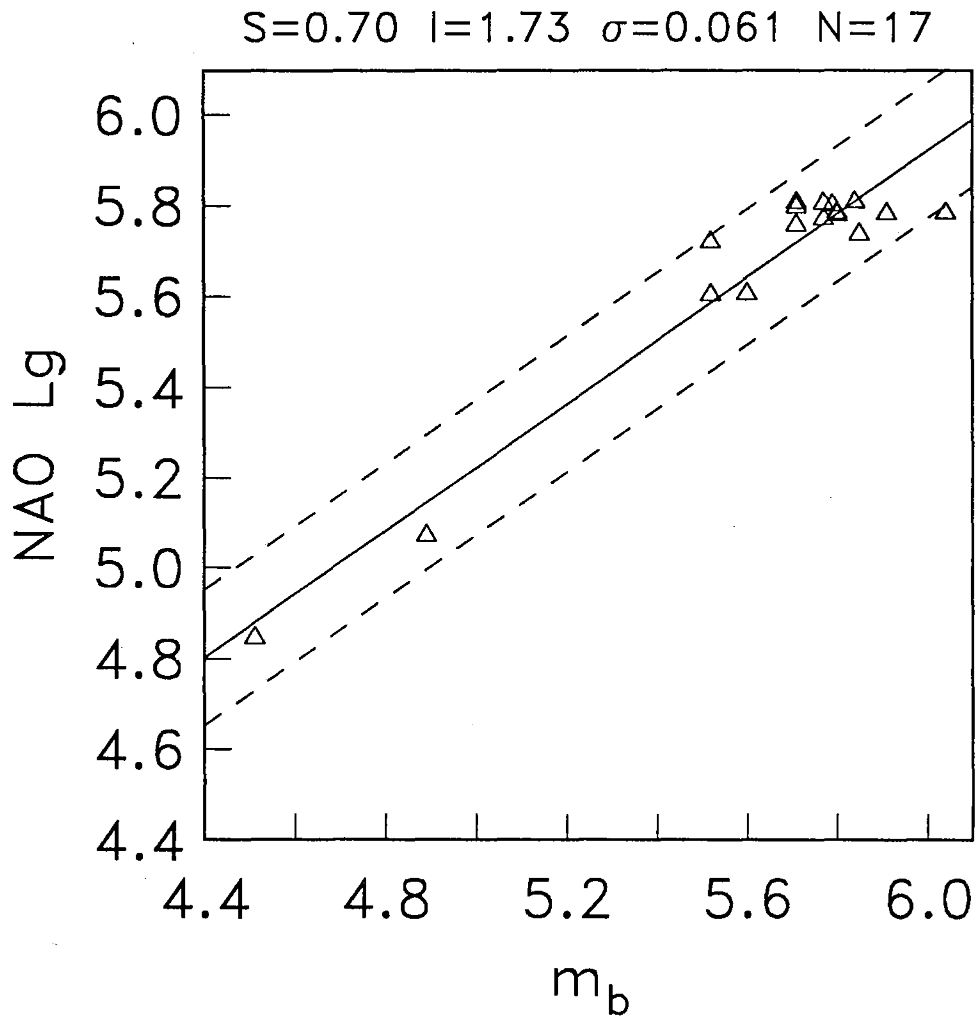

Fig. 7.1.5. Plot of NORSAR RMS Lg magnitude versus world-wide m_b. Note the much greater scatter in this plot compared to Fig. 7.1.4. Notational conventions are as in Fig. 7.1.4.

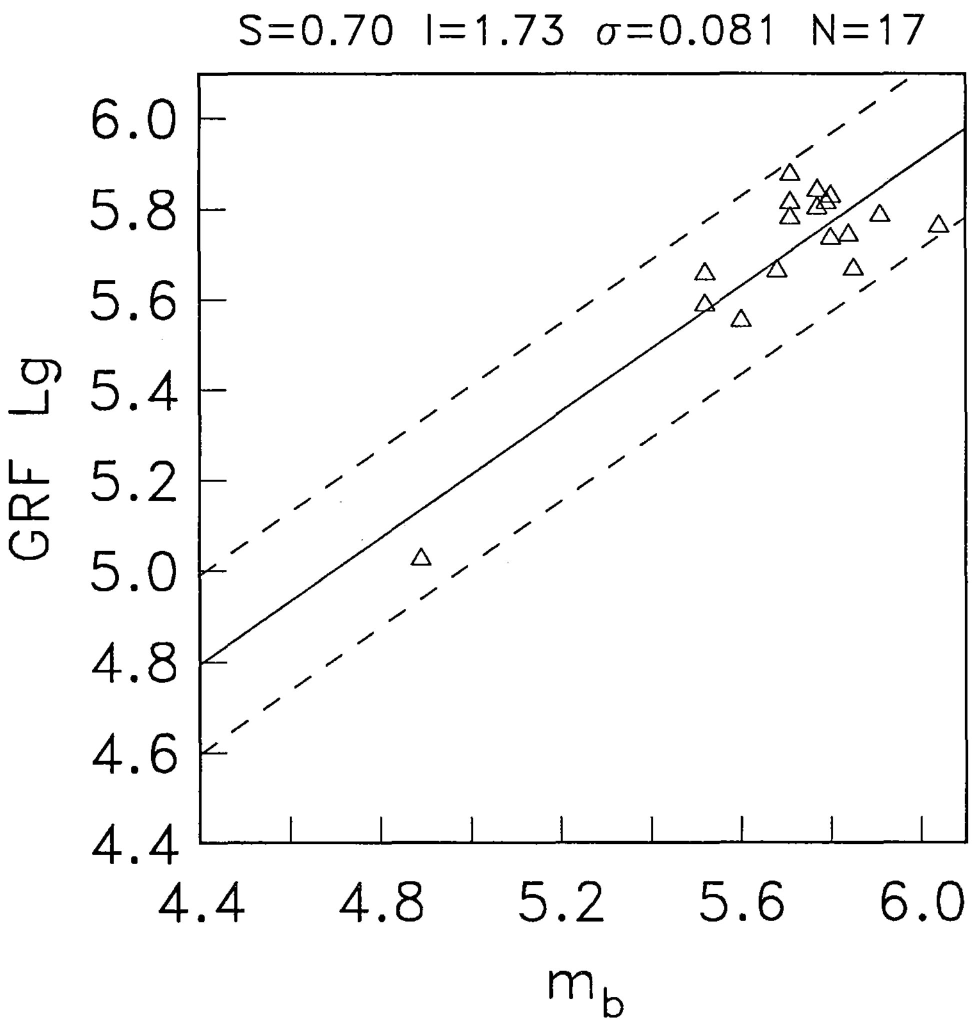

Fig. 7.1.6. Plot of Gräfenberg RMS Lg magnitude versus world-wide m_b. The scatter is comparable to Fig. 7.1.5. Notational conventions are as in Fig. 7.1.4.

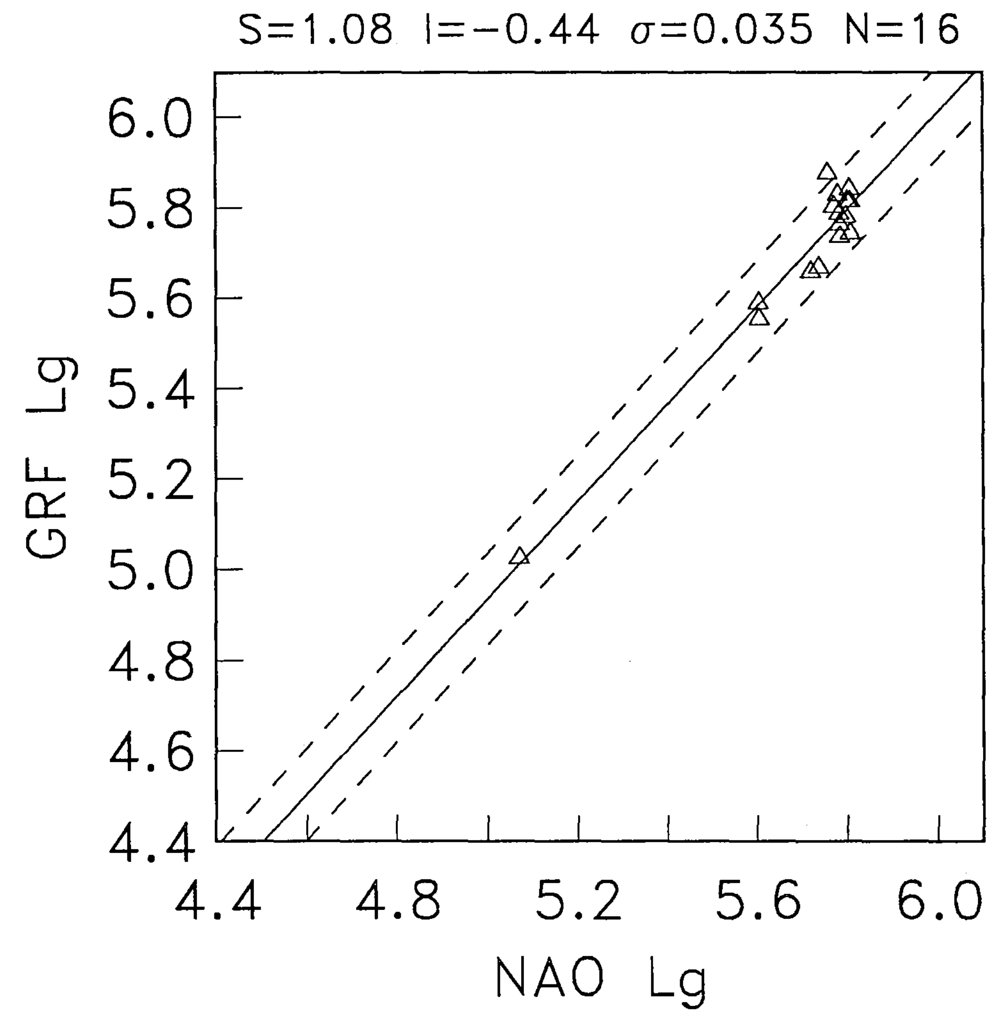

Fig. 7.1.7. Plot of Gräfenberg versus NORSAR RMS Lg magnitudes for all common events. Note the close correspondence, although one point in particular (Event 3) appears to be an outlier. Notational conventions are as in Fig. 7.1.4.

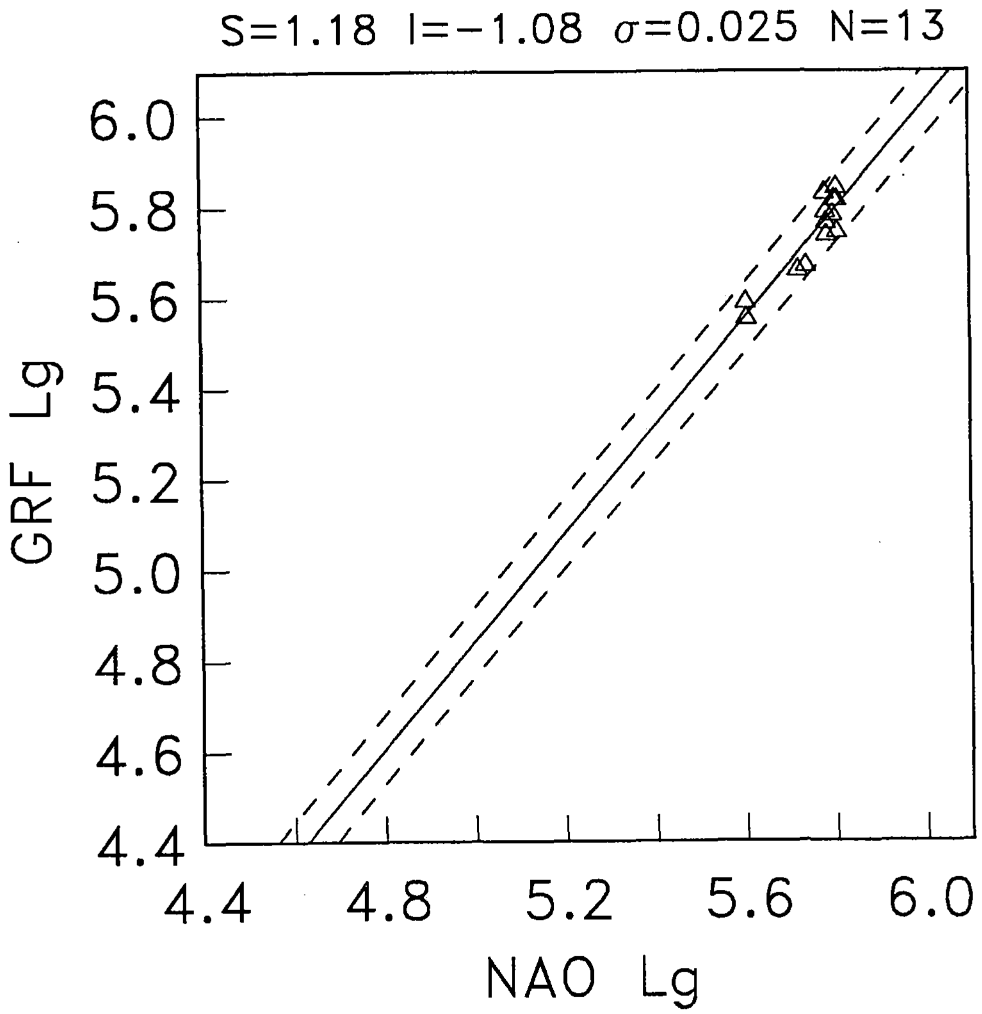

Fig. 7.1.8. Plot of Gräfenberg versus NORSAR RMS Lg magnitudes, using only events for which at least 5 GRF channels were available. Notational conventions are as in Fig. 7.1.4. Note that the orthogonal standard deviation is as low as 0.025. Also note that in spite of the very small range of magnitudes, the two arrays show mutually consistent trends.