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6.5 The Sumatra M_w=9.0 earthquake as a high-end test of NORSAR's processing capability

6.5.1 Background

The Sumatra earthquake hit on December 26, 2004, and caused the most damaging tsunami historically recorded, and at the time of writing nearly 300,000 casualties have been confirmed. The M_w=9.0 megathrust earthquake was the globally largest in 40 years, and ruptured nearly 1200 km of the subduction zone separating the India and Burma plates. It was recorded on the NORSAR arrays in Norway at approximately 84 degrees distance, and examples of recordings at NORSAR stations are shown in Fig. 4.4.7 in Section 4. The first P-arrival reached the NOA array approximately 12 minutes after the rupture started.

The earthquake occurred along the NW part of the Sumatra-Java subduction zone, and the general plate convergence in this region is oriented towards NNE with an average velocity of 5.5 to 6.0 cm/year. Recent studies in the region have revealed that the rupturing segment of the plate boundary has been locked for quite some time since three large earthquakes (M>8.0) that occurred in the same general area in 1833, 1861 and 1881 (Simoes et al., 2004; Ortiz and Bilham, 2003). Fig. 6.5.1 shows the recent seismicity in the region, including also the largest historical events.

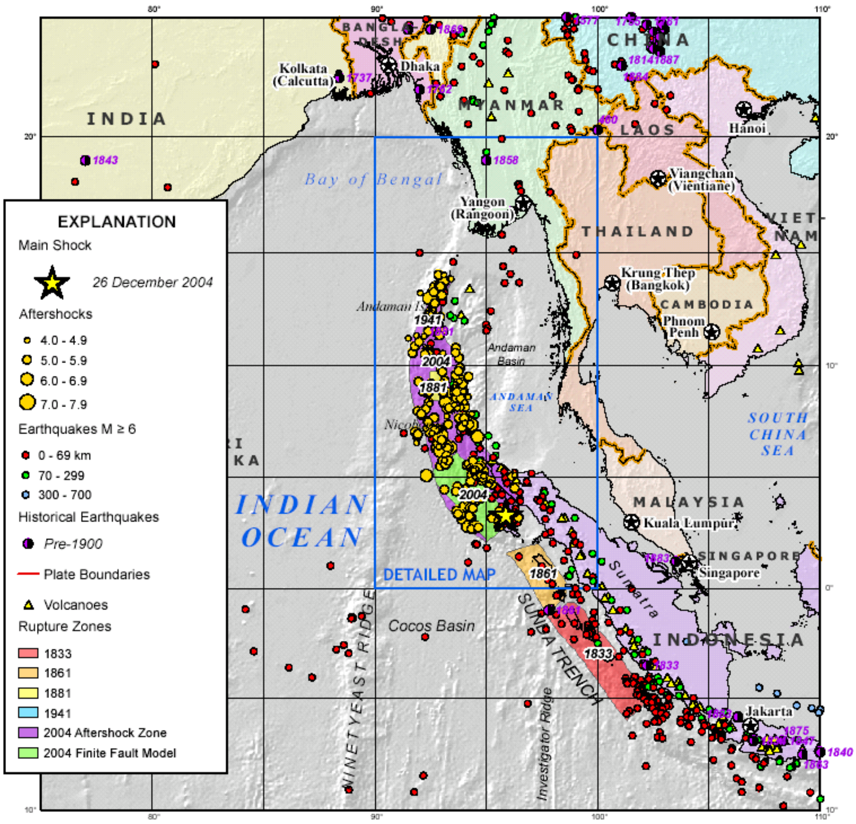

Fig. 6.5.1. Historical earthquakes and aftershocks following the 2004 megathrust earthquake. The historical large earthquakes are indicated with red circles. From USGS poster.

6.5.2 NORSAR's seismic processing system

NORSAR carries out routine detection processing and interactive analysis of seismic events, both globally (using mainly the teleseismic NOA array) and regionally (using the network of regional arrays in Fennoscandia and NW Russia). The processing algorithms in use at the NORSAR Data Center comprise the following steps:

- Automatic single array processing, using a suite of bandpass filters in parallel and a beam deployment that covers the main seismic phases for the region of interest.
- An STA/LTA detector applied independently to each beam, followed by broadband f-k analysis for each detected phase (best beam) in order to estimate azimuth and apparent velocity.
- Automatic single-array location of seismic events, by using a "beampacking" algorithm for teleseismic events and by associating P and S type phases for events at regional distances.
- For events at regional distances, the Generalized Beamforming (GBF) approach is used (Ringdal and Kværna, 1989) to associate phases from all stations in the regional network and thereby provide automatic network-based locations. Selected events are later analyzed interactively, and the results are published on the Internet.
- For teleseismic events detected by the NOA array, all detected events are reviewed by the analyst, and the reviewed solutions are published in the monthly NORSAR teleseismic event bulletin. This reviewed bulletin is also available on the Internet.

NORSAR has also developed an earthquake alert system, which has been described in a previous Semiannual Report (Schweitzer, 2003). In fact, two independent alert procedures are in effect at NORSAR: One is based on the automatic NOA teleseismic event list, and the second one uses the detection lists from all of the seismic arrays operated by NORSAR in order to provide automatic network-based event locations for large earthquakes. Whenever a large earthquake is detected by the system, alerts are generated automatically and sent to specific subscribers within minutes of the event. The performance of the alert system for the large Sumatra earthquake is described in more detail below. (The NOA processing include longer wait time to allow for teleseismic phase association.)

6.5.3 Processing of the 26 December earthquake

The travel time of seismic P-waves from Sumatra to Fennoscandia is about 12-13 minutes, and the time sequence of NORSAR's processing of the Sumatra earthquake is summarized in Table 6.5.1.

The first alert (based on joint processing of the Fennoscandian arrays) was issued at 01.18 GMT, i.e. about 19 minutes after the earthquake rupture started, and about 7 minutes after the signals were detected by the NORSAR array systems. The second alert (based on NOA single-array processing) was issued 2 minutes later, at 01.20 GMT.

Table 6.5.1 Time-line for NORSAR's processing of the Sumatra earthquake

Time (GMT) 26.12.04	Description
00.58.50	"Origin time" of the M=9.0 Sumatra earthquake. The fault rupture continued during 5-6 minutes.
01.10.45	Seismic P-wave arrival at the closest Fennoscandian array (FINES)
01.11.24	Seismic P-wave arrival at the large NOA array
01.18	Automatic alert message generated by the NORSAR NEWS system (based on network processing): 2004/12/26 00:59:04.97 4.59N 93.33E m_b=5.5 Message sent to EMSC as well as subscribing institutions/persons
01.20	Automatic alert message generated by the NOA single-array processing: 2004/12/26 00:58:59.4 2.7N 92.6E 33 m_b=6.3 Message sent to EMSC as well as subscribing institutions/persons

6.5.4 Epicenter locations

The source parameters for the main shock as provided by the NOA array's automatic location procedure and the US Geological Survey is provided in Table 1. The NOA solution locates the epicenter 378 km to the NW of the USGS epicenter, which is regarded as acceptable for a fully automated solution generated only minutes after the first arrivals hit the stations east of Hamar, Norway.

The automatic NOA solutions of the aftershocks were compared with the multi-station QED solutions published by USGS, and a median epicenter difference of 271 km was found between the two groups. Fig. 6.5.2 compares the aftershocks as located by the European-Mediterranean Seismological Centre (EMSC) with the NOA automatic solutions, and essentially shows the same situation. While the greater spread in the automatic NORSAR locations is evident, the location estimates concentrate well around the main rupture zone, lending credibility to the basic processing algorithms.

Table 6.5.2. Source parameters from NOA array's automatic single array location compared with the reviewed solution of USGS

Source parameter	NOA (automatic)	USGS (Manually corrected)
Magnitude	6.3 m_b	9.0 M_w
Origin time	Dec. 26; 00:58:59.4	Dec. 26; 00:58:53
Depth	33 km	30 km
Latitude	2.70N	3.307N
Longitude	92.60E	95.947E

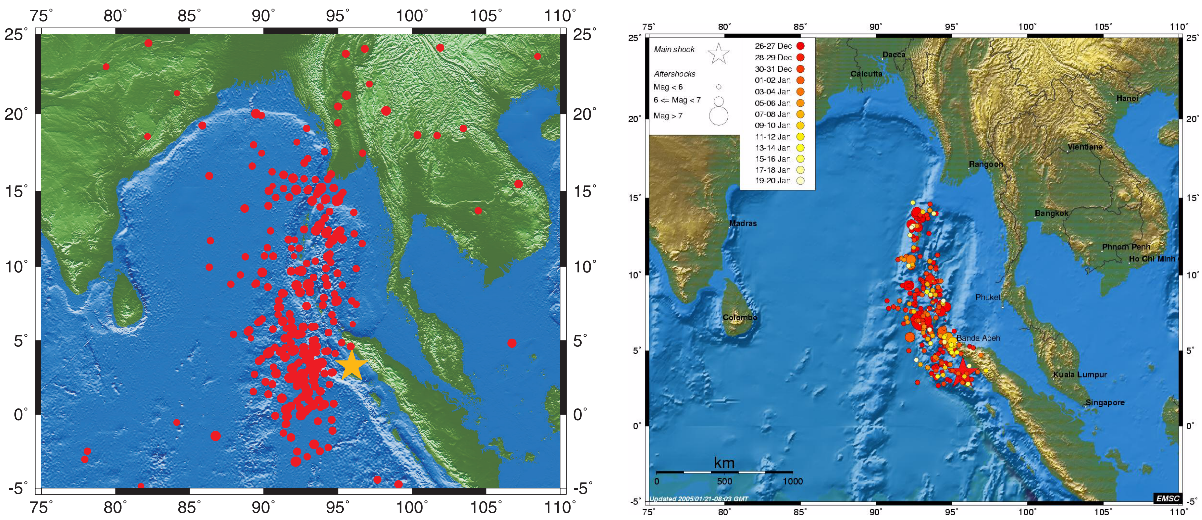

Fig. 6.5.2. Left: Automatic one-array NOA locations. Right: The aftershock distribution in the EMSC database (reviewed). Both maps show aftershock data recorded until January 20.

6.5.5 Aftershocks

The sensitivity of the NORSAR systems is indicated by the large number of aftershocks recorded. Until January 20, 2005, 736 aftershocks were detected and located by the NOA array as shown in Fig. 6.5.2. The NOA reviewed bulletin contained 274 aftershocks during the first day alone, and Fig. 6.5.3 shows the number of aftershocks during the first 21 days after the main earthquake.

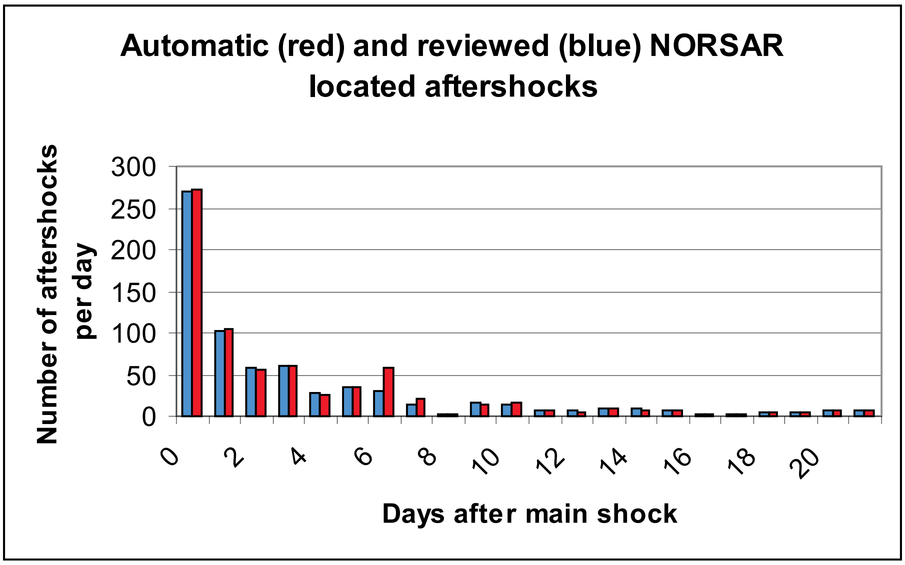

Fig. 6.5.3. Number of aftershocks recorded and located by NORSAR the first 21 days after the main event (from the automatic (red) and the reviewed (blue) bulletin)

6.5.6 Magnitudes

The epicenter to station azimuths for the Fennoscandian stations were 330 - 348 degrees, which is in the direction of the main rupture. At this time, we refrain from speculations on how this affected the magnitude calculations, and we refer to Schweitzer and Kværna (1999) for further discussions of this issue.

As described above, the two automatic systems for alerts reported m_b magnitudes of 5.5 and 6.3. The m_b 6.3 is obtained from the automatic large aperture array NOA processing. The amplitude is measured on a filtered beam (0.5-2.0Hz), and the time-window rule for picking the peak amplitude for the m_b measurement is to stay within 5 seconds after the P onset. An alert message reporting m_b magnitudes from 5.5 to 6.3 from a subduction zone is quite normal, and would not be considered as a possible catastrophic earthquake. In the search for other magnitude procedures, we therefore also measured manually the body wave maximum amplitude within 2 minutes after the P onset, and Table 6.5.3 show the results for m_b as well as for M_S measurements. As expected the m_b values are much larger than those measured during the first 5 seconds.

We normally see that large earthquakes have long P coda, and we see from Table 6.5.3 that extending the search time window for magnitude calculation results in significantly higher magnitudes. These results may indicate the need for a 2 step magnitude calculation: for the first alert messages, the first value (5 sec) is necessarily used, however, the first alert may be followed by a secondary processing (e.g. after 2 minutes) where additional measurements over longer time windows after the P arrival is used to verify or adjust the magnitude.

Table. 6.5.3. The m_b measurements were done in filter band 0.5-2Hz, whereas Ms was measured on unfiltered data

Station	m_b < 5 sec	m_b < 2 min	M_S
ARE0_bz	6.39	7.36	Clipped
SPA0_BHZ	6.58	7.72	9.05
NC405_bz	6.17	6.84	8.80
NC602_bz	6.10	7.21	9.03
FIA1_bz	6.28	7.28	Clipped
HFC2_bz	6.68	7.53	Clipped
JMIC_BHZ	6.66	7.24	Clipped

Finally, Fig. 6.5.4 compares 288 magnitude pairs in the aftershock sequence and demonstrate that the USGS reported magnitudes are systematically larger than the one-array NOA magnitudes. The difference is particularly pronounced at low magnitudes, and this illustrates the well-known "network magnitude bias" problem. In fact, the NOA single-array magnitudes are more consistent over the entire magnitude range than the network-based USGS magnitudes. Fig. 6.5.5 summarizes the magnitude differences in a cumulative probability distribution.

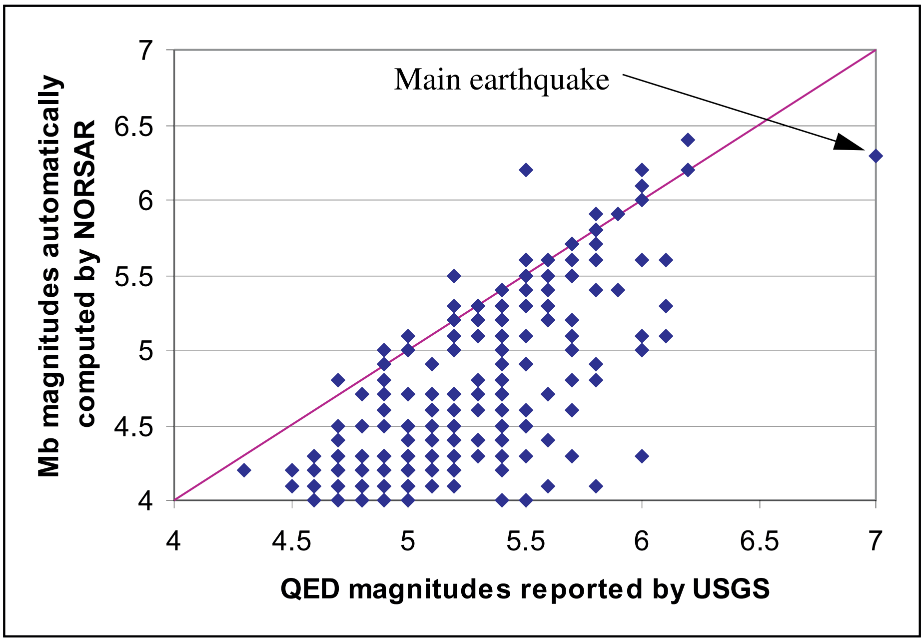

Fig. 6.5.4. Magnitudes for selected aftershocks (origin times within 60 seconds) for automatic NOA locations and QED reports from USGS.

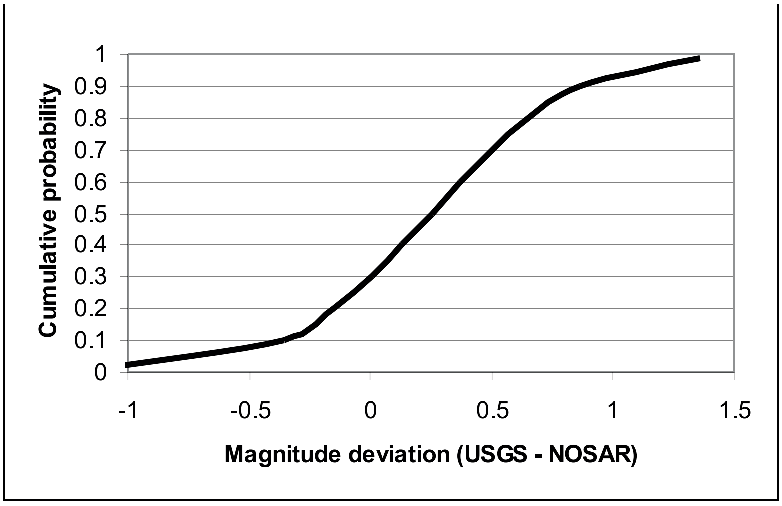

Fig. 6.5.5. Fig. 6.5.5. Magnitudes for selected aftershocks for automatic NOA locations and QED reports from USGS. Pairs of the earthquakes were matched if their origin time difference (NOA-QED) was within 60 seconds.

6.5.7 Conclusions

The Sumatra earthquake was the largest earthquake ever recorded by NORSAR, and consequently represented a test of the current instrumentation and processing algorithms. The alert system functioned well for the earthquake with reasonably precise location information relayed about 7 and 9 minutes after the first arrivals were recorded in Finland and Norway. The automatic magnitude estimates were considerably lower than later interactive measurements. While this is no surprise, it certainly represents a challenge for improving on magnitude determination algorithms for large earthquakes. Until January 20, 2005, 736 aftershocks were detected and located on the NOA array, and the automatic locations by and large delineate the main rupture.

Following this experience, some challenges for new developments have been identified: a) The processing could be optimized to provide the alert with a delay of some seconds rather than 7 and 9 minutes after data are recorded. Clearly, access to data from local or regional stations would enable even earlier alerts. b) The magnitude estimation (based on P-waves) should be improved for large events. Among the factors to take into account here are both the spectral properties of the signal and the duration of the P-wave train.

In summary we may state that:

- the NORSAR alert bulletins were functioning as intended, and with the appropriate precision for such distances.
- The processing of both main and aftershocks indicates adequate processing.
- The automatically computed m_b magnitudes are in principle not adequate for this size earthquakes.

- The automatic system may be improved on two particular targets: a) Improve the speed of the processing and b) develop/implement new magnitude estimation algorithms. For the latter it is possible to design a two-step alert system: the first step will be as today, however a delayed reprocessing (e.g. after 2 minutes) can be used to recalculate the magnitude from a longer time window.

References:

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