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# Semiannual Technical Summary

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## 6.2 Late stages of the Storfjorden, Svalbard, aftershock sequence

### 6.2.1 Introduction

On 21st February 2008, a strong earthquake of moment magnitude Mw = 6.1 occurred in the offshore area of Storfjorden, Svalbard. The event was followed by a vast aftershock sequence, recorded by the seismological stations in the broader region. A special investigation of the first seven months of this earthquake sequence was facilitated by the coinciding conduction of an International Polar Year (IPY) project (Schweitzer et al., 2008), which included the deployment of several temporary installations in the region. This study (Pirli et al., 2010), which involved the location of a large number of aftershocks and the calculation of moment tensors for the main event, showed that the seismic rupture occurred on an unmapped, oblique-normal fault, probably of NE-SW trend and steep SSE dip (Regional and Teleseismic MTs in Fig. 6.2.1). It also revealed strong indications of secondary activations within the same aftershock volume, suggested by the spatial distribution of the events and waveform similarity.

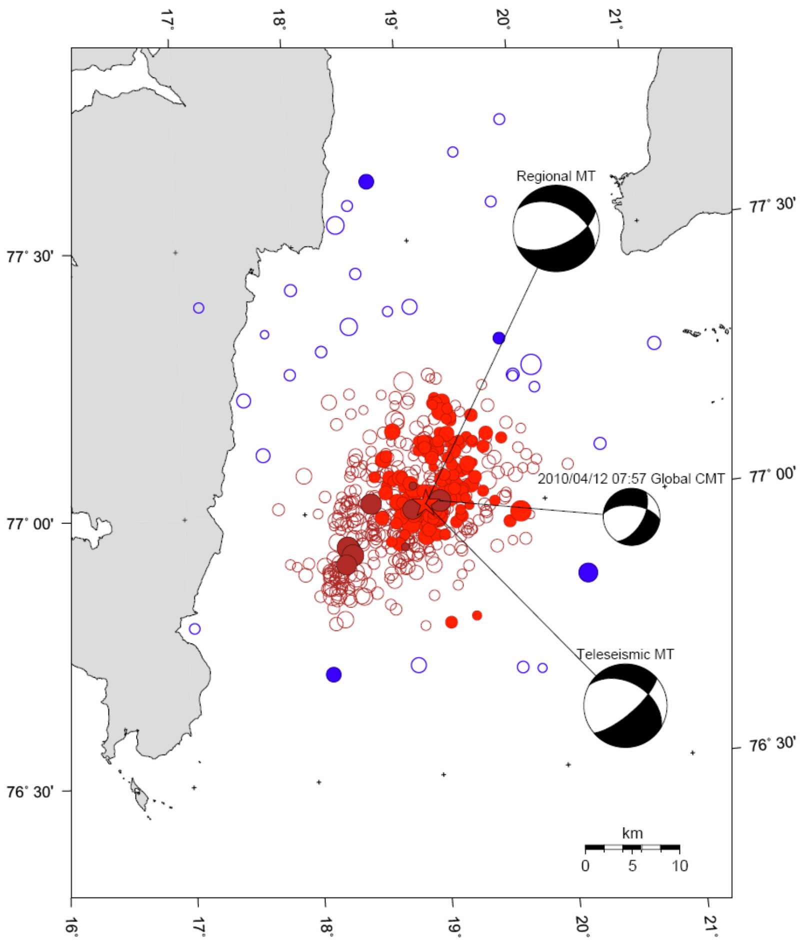


*Fig. 6.2.1. Spatial distribution of events in Storfjorden, from the 21st February 2008 mainshock (red star) to the end of November 2010, and focal mechanisms from Pirli et al., 2010. The focal mechanism of the 2010/04/12 07:57 event is calculated by the Global CMT Project. NORSAR reviewed bulletin solutions are shown as open circles, while filled circles denote relocated epicentres. Red circles are relocated events from Pirli et al. (2010), dark red are relocated events after October 2008, and blue colour is used to note events that lie outside the main aftershock volume.*

### 6.2.2 Spatio-temporal evolution of the sequence after October 2008

Although most of the IPY related installations were demobilised in autumn 2008, the area remained under focus within the framework of routine seismic monitoring of the European Arctic. This revealed persistent seismic activity in Storfjorden on an almost continuous basis, still ongoing at the time when this report is being composed. The spatial distribution of this seismicity is displayed in Fig. 6.2.1. The image is based partly on the listings of NORSAR's regional, analyst reviewed bulletin (http://www.norsardata.no/NDC/bulletins/regional/), which contains events with an automatic magnitude larger than 2.0 (open circles of any colour), and partly on the results of Pirli et al., 2010 (red circles) for events up to the end of September 2008. Relocated epicentres for events after this time interval, which were derived with the use of additional data, different velocity models and/or different phase identification compared to the routine analysis, are noted in dark red. A different colour (blue) is used to indicate seismic events that fall outside the main aftershock volume. The most interesting feature of the map is the abundance of epicentres SW of the volume located by Pirli et al. (2010). In addition to the epicentre distribution, the focal mechanism of the 2010/04/12 07:57 M 4.9 event is shown, as determined by the Global CMT Project (http://www.globalcmt.org/). Although this event occurred during the later stages of the sequence, it is located very close to the epicentre of the mainshock and has a focal mechanism which describes very similar faulting.

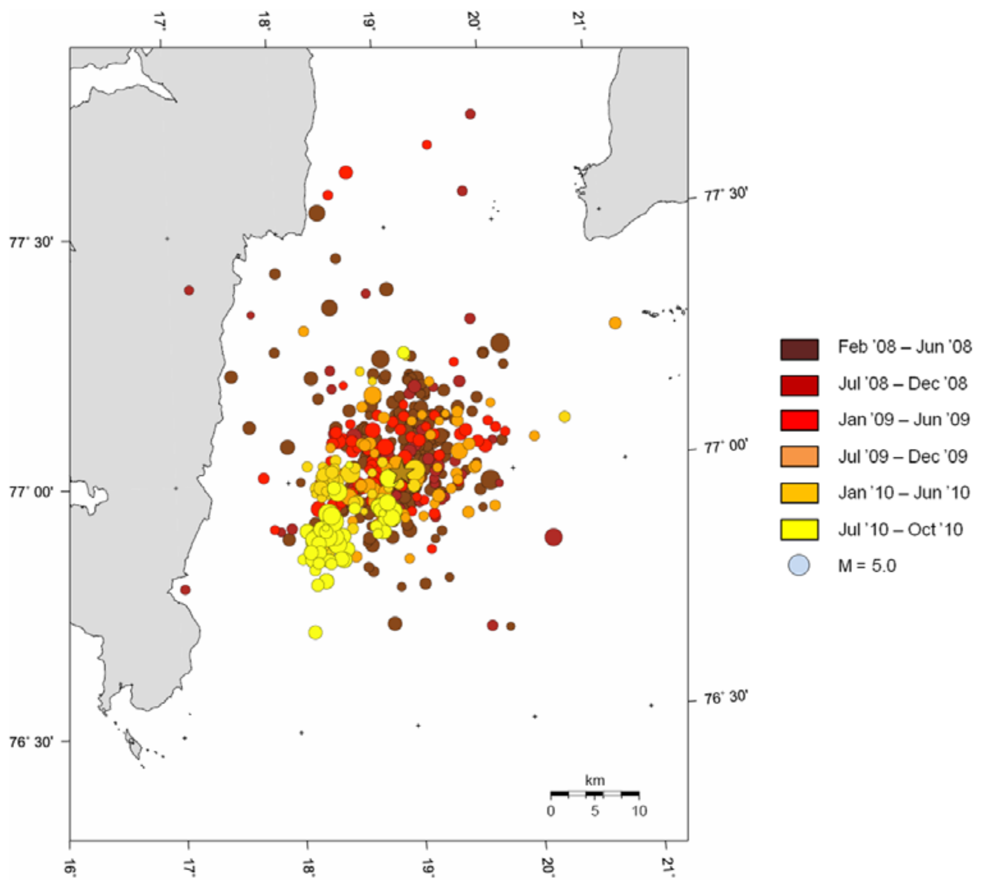


*Fig. 6.2.2. Spatiotemporal distribution of events in Storfjorden between 21/02/2008 and 30/11/2010, based on the listings of NORSAR's regional reviewed bulletin and Pirli et al., 2010. The mainshock is noted by a star, while aftershock epicentres are scaled according to magnitude.*

A colour scale is used in Fig. 6.2.2 to map the spatiotemporal distribution of the events shown previously in Fig. 6.2.1. It is clearly obvious that while seismic activity in the area of the 21st February 2008 main event persists, the main volume of activity within the year 2010 and in particular its second half, is concentrated in an area SW of the previous aftershock volume. This reveals the existence of a new source of activity, which lies either on the south-westerly extension of the seismogenic fault suggested by Pirli et al. (2010) or a neighbouring tectonic structure.

The distribution of the number N of seismic events per day is shown in Fig. 6.2.3, expressed in days after the occurrence of the February 2008 main event. Alternatively, time is shown in years, and the distribution of observed event magnitudes M with time is additionally plotted. The distribution is again based on NORSAR's regional reviewed bulletin and Pirli et al., 2010. The daily number of events decreases very rapidly already in the early stages of the aftershock sequence, however the activity persists on a low level. Outbursts can be observed in 2009 and a larger activation is observed within the second half of 2010. It is also notable that this late activity is characterised by larger average magnitude levels compared to the time before late spring 2010. This is demonstrated clearly by the fact that excepting the February 2008 main-shock, only 12 aftershocks of magnitude larger than 4.0 were observed until summer 2010, whereas the same number of events within the same magnitude range was observed during the remaining 5 months of 2010.

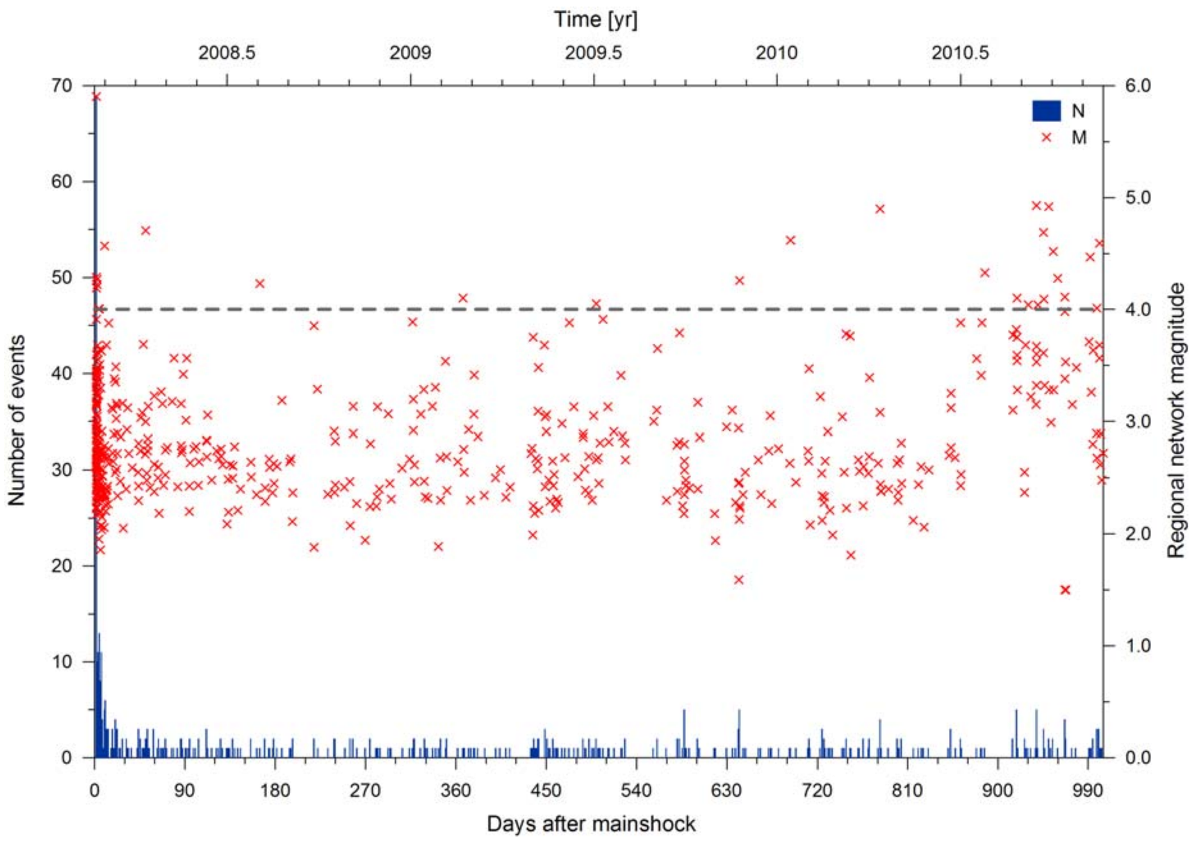


*Fig. 6.2.3. Number of events per day after the occurrence of the 21st February 2008 mainshock and event magnitude distribution in time, based on the listings of NORSAR's reviewed bulletin and Pirli et al., 2010. The dashed line marks the magnitude 4.0 threshold.*

### 6.2.3 Waveform cross-correlation detector results

An alternative image of the evolution of the sequence is provided in Fig. 6.2.4 (light coloured line). Since NORSAR's reviewed bulletin has a magnitude threshold of 2.0, this image of the sequence is incomplete. To retrieve information about the distribution of events of smaller magnitude, a waveform cross-correlation detector (Gibbons and Ringdal, 2006) on the data of the broadband sensor at the Polish Polarstation Hornsund (HSPB) was used. A number of events spanning the entire length of the sequence (master events) were selected to detect other similar events. Information about these 23 events can be found in Table 6.2.1. The result of the use of the employed master events (red stars in Fig. 6.2.4) is the dark coloured line, which clearly demonstrates the much larger number of events associated with this activity in Storfjorden than revealed from the listings of NORSAR's reviewed bulletin. The step-like jumps in the distribution correspond to rapid increases in the number of earthquakes, the most striking of them being the one observed at about 780 days after the magnitude 6.1, February 2008 mainshock (spring 2010). Changes in the slope of the "linear" part of the curve indicate distinct branches of activity. Four main branches can be discerned after day 200 from the occurrence of the mainshock, with the following approximate definitions: one from day 200 to day 270 (end of August 2008 to mid November 2008), one from day 270 to day 500 (July 2009), a third one from day 500 to day 900 (August 2010) and a fourth one from day 900 on.

**Table 6.2.1. The master events used for aftershock detection**

| origin time | latitude (°) | longitude (°) | M | N detections |
|---|---|---|---|---|
| 2008-052:02.53 | 77.072 | 18.008 | 3.6 | 2 |
| 2008-053:04.24 | 77.195 | 19.138 | 2.7 | 151 |
| 2008-057:15.56 | 76.977 | 19.093 | 2.9 | 88 |
| 2008-060:13.04 | 77.042 | 18.911 | < 2.0 | 65 |
| 2008-071:06.05 | 77.134 | 19.215 | 3.4 | 11 |
| 2008-162:04.43 | 77.099 | 19.210 | 2.8 | 5 |
| 2008-333:03.29 | 77.050 | 19.095 | 3.1 | 36 |
| 2009-002:16.52 | 77.057 | 18.588 | 3.2 | 103 |
| 2009-063:08.44 | 77.038 | 19.048 | 3.4 | 84 |
| 2009-133:19.58 | 77.074 | 18.412 | 3.0 | 35 |
| 2009-180:17.38 | 77.026 | 18.890 | 2.3 | 4 |
| 2009-327:04.22 | 76.986 | 19.501 | 2.5 | 15 |
| 2010-030:16.04 | 76.950 | 18.794 | 2.7 | 28 |
| 2010-103:10.59 | 76.950 | 18.847 | 2.4 | 304 |
| 2010-234:17.46 | 76.943 | 18.787 | 3.8 | 117 |
| 2010-270:12.09 | 76.919 | 18.379 | 4.9 | Itself |
| 2010-270:22.11 | 76.899 | 18.309 | 3.3 | 7 |
| 2010-275:01.34 | 76.998 | 18.896 | 4.5 | 4 |
| 2010-275:01.47 | 76.936 | 18.798 | 3.3 | 7 |
| 2010-286:08.39 | 76.907 | 18.309 | < 2.0 | 5 |
| 2010-287:18.09 | 76.929 | 18.815 | < 2.0 | 20 |
| 2010-320:22.46 | 76.879 | 18.191 | 3.7 | 12 |
| 2010-320:23.59 | 76.883 | 18.192 | 3.6 | 2 |

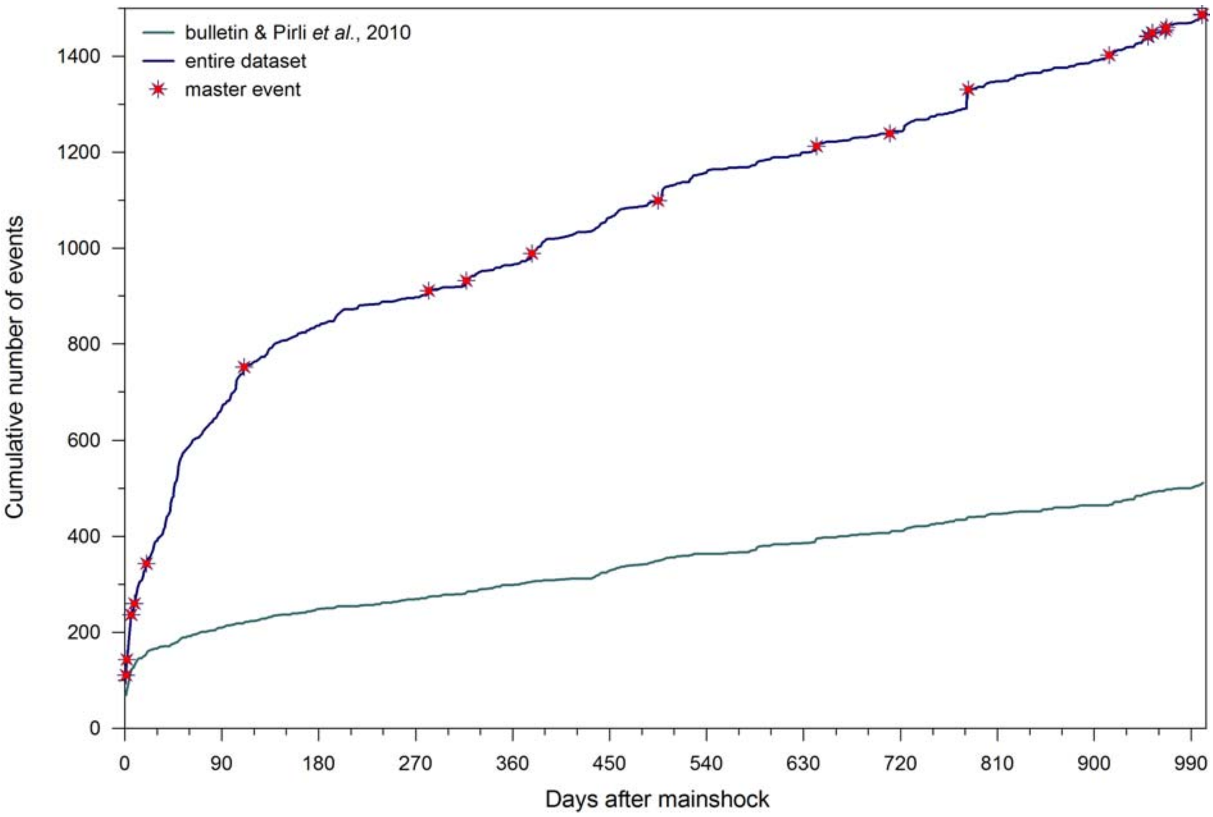


*Fig. 6.2.4. Cumulative number of events for the activity in Storfjorden, Svalbard, against time in days after the 21st February 2008 mainshock, for the dataset of located earthquakes (NORSAR's reviewed bulletin and Pirli et al., 2010) – light coloured line – and for a dataset resulting from the use of a waveform cross-correlation detector, with 23 master events so far – dark coloured line. The approximate time of occurrence of the selected master events is noted with red stars.*

A more detailed image is provided in Fig. 6.2.5, which is the corresponding distribution to that of Fig. 6.2.3, this time based on the entire dataset associated with the Storfjorden activity, which includes NORSAR's regional bulletin and Pirli et al. (2010) data, as well as the events identified by the cross-correlation detector. The obtained image of aftershock occurrence rate is quite different to that of Fig. 6.2.3, especially for the first 120 days of the series, when many more events have been recovered. The remaining time interval, which exceeds two years, is again characterised by the appearance of short-lived peaks that are, in most cases, related to aftershocks of larger magnitude. The most striking of them is the peak observed 780 days after the February 2008 event, in April 2010. It is associated with the 12th April event of magnitude 4.9 (see Fig. 6.2.1 for focal mechanism) and its aftershocks, however, the rate of event occurrence resumes its previous levels almost immediately after the two-day increase. Another interesting feature of the distribution, which was already apparent in Fig. 6.2.3, is the activity after August 2010. Despite the fact that several master events from this time interval were used, they yielded very few detections; almost none in some cases. Thus, we can safely conclude that during this latest stage the character of the activity is significantly changing, with the occurrence of many small distinct branches, which contain mainly higher magnitude members.

It should be stressed here that the obtained image is a direct consequence of a number of parameters. The most decisive is the number and character of the selected master events, since not all of them are equally productive and/or representative of the diversity of waveforms within the sequence, as shown in this case by Table 6.2.1. The SNR threshold used for the detection process and the minimum acceptable cross-correlation coefficient, chosen to ensure the validity of the results, may also cause some loss of information, however a balance has been sought between discarding true detections and eliminating the false ones. In addition, all the above points are strongly influenced by the noise conditions at HSPB. Thus, the event catalogue consisting of the achieved detections is not complete, however care was taken that it is representative for the wide variety of waveforms observed throughout the Storfjorden activity, so some safe conclusions can be derived for the overall distribution.

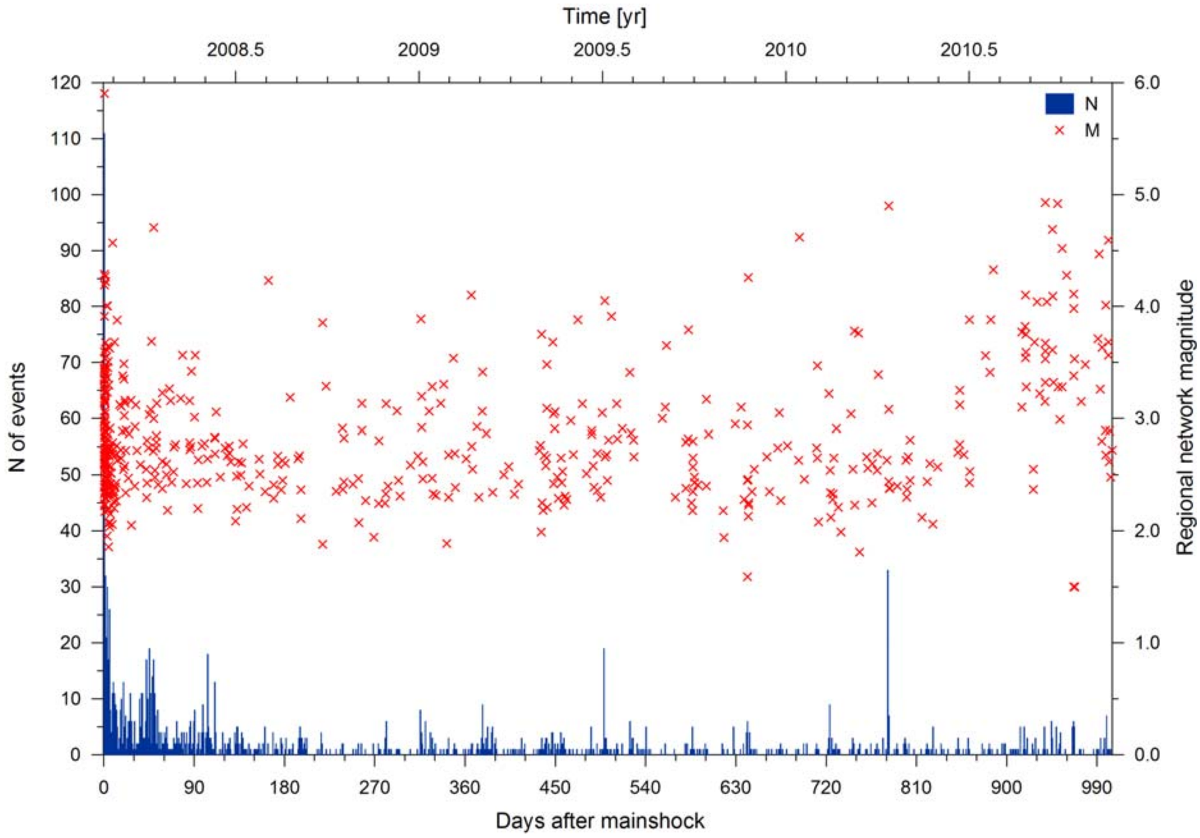


*Fig. 6.2.5. Number of events per day after the occurrence of the 21st February 2008 mainshock, based on the listings of NORSAR's reviewed bulletin, Pirli et al. (2010) and the results of the waveform cross-correlation detector. In addition, event magnitude distribution in time is shown for events in NORSAR's bulletin and Pirli et al., 2010.*

The three consecutive panels of Fig. 6.2.6 (one for each year) show the distribution with time of the waveform cross-correlation (CC) coefficient for those master events that provided detections. After some visual inspection of detector results, a CC-coefficient of 0.60 was decided as a threshold to eliminate erroneous detections. The time scale is uniform to facilitate a meaningful comparison between the three distributions, while different symbols are used for the detections of different master events. Three main time intervals can be distinguished, based on the "universality" of the employed master events: (a) the early stages of the sequence, represented by master events in 2008, which yield detections almost exclusively within the same time period, (b) a long time interval including 2009 and 2010 until autumn, when employed templates produce detections from almost the entire time length under discussion, and (c) the last two months when master events appear to be associated with only a very small number of earthquakes spaced closely around them in time.

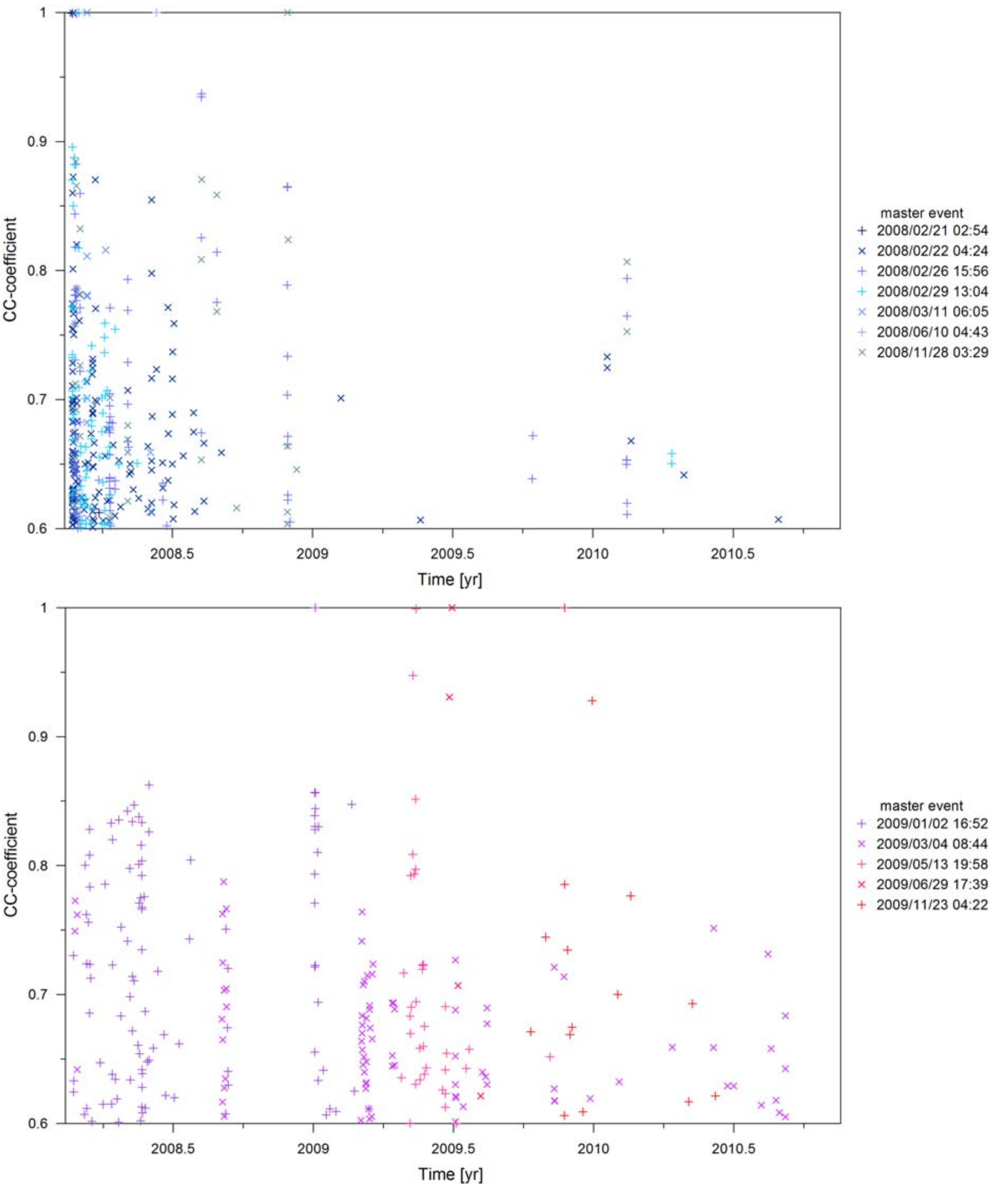


*Fig. 6.2.6. Temporal distribution of the waveform CC-coefficient for the 22 of the 23 master events used within this study that yielded detections. A threshold of 0.60 was applied to ensure the validity of the results. Top diagram shows the 2008, at bottom the 2009 and on top on the next page the 2010 master events. Each master event is shown with a different symbol.*

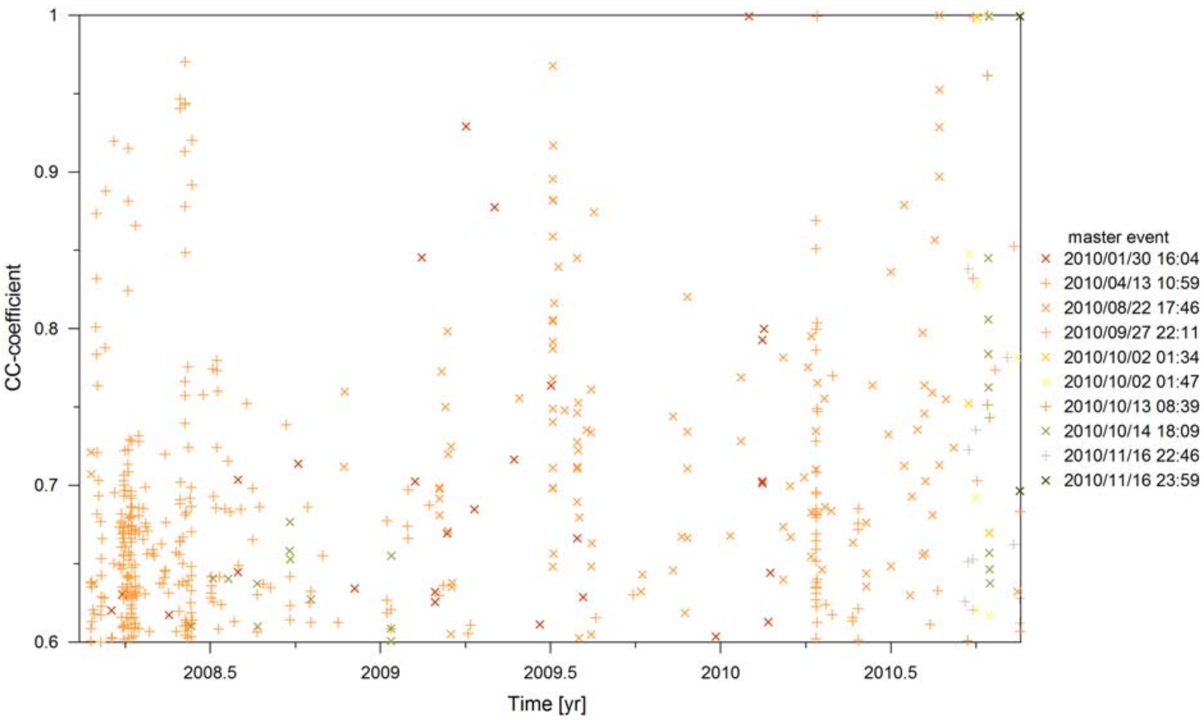


*Fig. 6.2.6 Continuation from the previous page.*

A closer look into the distributions of Fig. 6.2.6 reveals some expected and some more unusual features. Larger magnitude (e.g., M > 4.0) events are known to be non productive templates and this is verified here. The reason for their selection was to investigate their similarity to other events of the same magnitude order within the sequence; all of the larger events (M > 4.5) appear to be unrelated, suggesting a strong fragmentation of the aftershock region. The first master event (see Table 6.2.1), which is the first significant aftershock of the entire series, is similar only to one more event, a fact that should not be attributed exclusively to its size, but most probably to the conditions and operating mechanisms during the very initial stages of the sequence. The rest of the early master events are quite productive, but only for a limited time interval. What is quite unusual is the very small number of similar events detected by most of the latest templates (from October 2010 on). The fact that they do not correlate with any earlier activity is hardly surprising, since these events are located SW of the main aftershock volume (see Fig. 6.2.2). However, even when their own time period is considered, only very few low magnitude events were detected, suggesting that the image of the activity obtained in Fig. 6.2.5 is quite accurate. Those of the latest master events that share some similarity with the earlier activity, are the ones located within the initial aftershock region (see Fig. 6.2.1 for distribution in Pirli et al., 2010). So, the combination of the spatiotemporal distribution of the events and waveform similarity information provides a good overview of the evolution of the series.

At this point it should be stressed that the observed dissimilarity between the events latest in the series and the rest of the activity is not attributed solely to a difference in the S-P arrival time difference (note that entire waveforms are used for detection purposes). This can be demonstrated by Fig. 6.2.7, where entire waveforms for the three components of station HSPB are shown, band-pass filtered between 3 and 8 Hz. There are three waveform groups, sorted by component, while events are sorted with time, starting with the February 2008 main event on top of each group. The second event is the 12th April 2010, magnitude 4.9 event, followed by events on 15th September 2010 05:56, 27th September 2010 12:09 and 6th October 2010 09:43. Besides the obvious S-P time difference between the upper two and the lower three events, it is obvious that the two groups contain different phases, while variations in the radiation pattern are also suggested by the different amplitude levels for P-type phases on the horizontal components. It is unclear whether this signifies a larger diversity in focal mechanism, which would point to a tectonic structure of different geometry to that of the seismogenic fault, or this is an effect of the different location and/or probable difference in focal depth between the two groups.

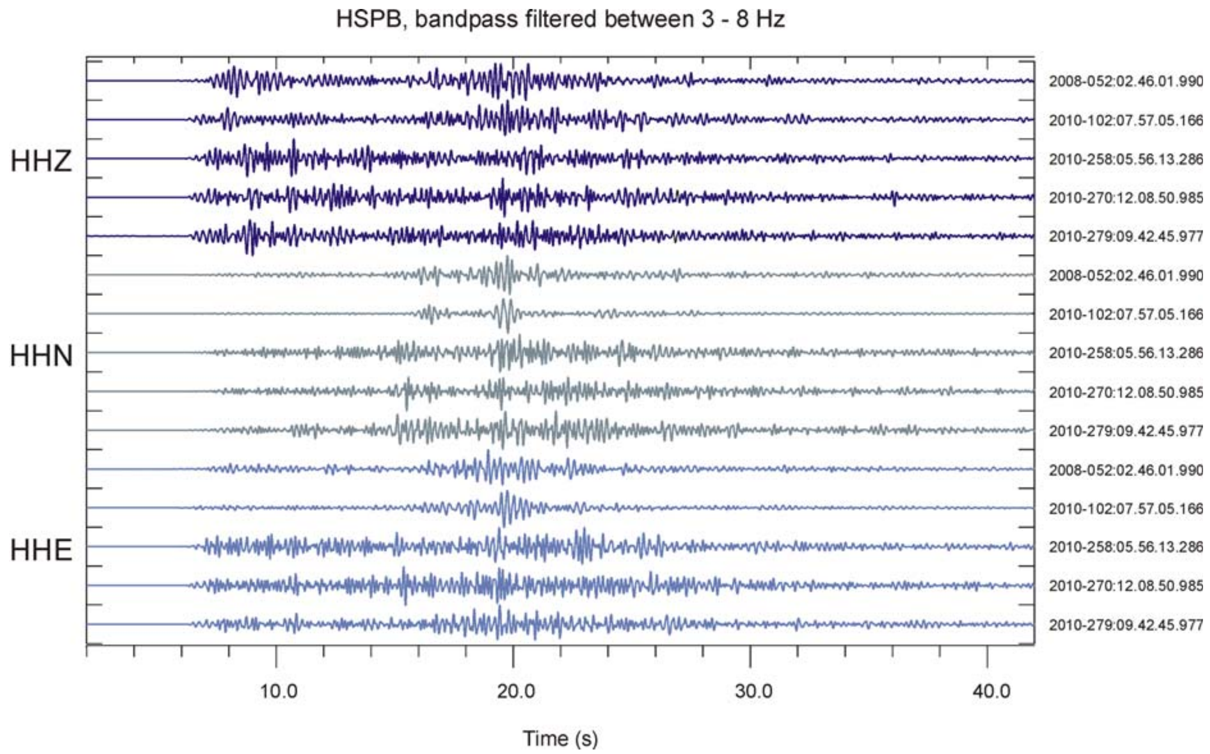


*Fig. 6.2.7. Waveforms of Storfjorden events as recorded at HSPB, band-pass filtered between 3 and 8 Hz. The events pictured here are the 21st February 2008 mainshock (2008-052 02:46, Mw 6.1), the 12th April 2010 event (2010-102 07:57, M 4.9), the 15th September 2010 event (2010-258 05:56, M 4.9), the 27th September 2010 event (2010-270 12:09, M 4.9) and the 6th October 2010 (2010-279 09:43, M 4.3) event.*

### 6.2.4 Conclusions

Summarising all the points made above, monitoring of the persisting seismic activity in the area of Storfjorden, Svalbard, leads us to the conclusion that this is a continuation of the February 2008 earthquake series. However, from autumn 2010 on, the main part of the activity is concentrated in an area SW of the original aftershock region, revealing a new source, either on a different part of the fault that gave the magnitude 6.1 mainshock in 2008 or on a neighbouring tectonic structure. A solid conclusion on the characteristics and nature of this source can only be derived from the calculation of focal mechanisms for the largest, most recent events. It is clear though, based on waveform similarity and the spatio-temporal distribution of these late events, that the mechanism behind their occurrence is different than that of the earlier stages of the series. The large magnitudes (M > 4.0) observed during this latest stage further suggest that the region is far from reaching equilibrium.

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**Berit Paulsen**
**Johannes Schweitzer**

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