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Inferring Aftershock Sequence Properties and Tectonic Structure Using Empirical Signal Detectors

William N. Junek · Tormod Kvaerna · Myrto Pirli · Johannes Schweitzer · David B. Harris · Douglas A. Dodge · Mark T. Woods

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Abstract Seismotectonic studies of the 2008 Storfjorden aftershock sequence were limited to data acquired by the permanent, but sparse, regional seismic network in the Svalbard archipelago. Storfjorden's remote location and harsh polar environment inhibited the deployment of temporary seismometers that would have improved observations of sequence events. The lack of good station coverage prevented the detection and computation of hypocenter locations of many low magnitude events (mb < 2.5) in the NORSAR analyst reviewed bulletin. As a result, the fine structure of the sequence's space-time distribution was not captured. In this study, an autonomous event detection and clustering framework is employed to build a more complete catalog of Storfjorden events using data from the Spitsbergen (SPITS) array. The new catalog allows the spatiotemporal distribution of seismicity within the fjord to be studied in greater detail. Information regarding the location of active event clusters provides a means of inferring the tectonic structure within the fault zone. Results show the sequence is more complex then suggested by the analyst reviewed catalog. The distribution of active clusters in the fjord suggests the fault zone has a SW-NE trending en echelon structure, which supports the orientation of the relative relocation catalog and the mixture of strike-slip and normal focal mechanisms.

Keywords Correlation Detectors · Subspace Detectors · Aftershock Sequence · Tectonics · Seismicity

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1 Introduction

Aftershock sequences are typically studied using a dense network of seismometers. The sensor network generally consists of existing instruments and temporary stations whose deployment is optimized for studying a particular sequence. This provides seismologists with the means to detect low magnitude events, compute more accurate hypocenter locations, and generate relative relocation catalogs. Results provide insight into the seismotectonics of the region and are useful for seismic hazard studies. The remote location of some aftershock sequences makes the deployment of temporary sensors impractical. Factors inhibiting such deployments include: harsh environmental conditions (e.g., polar climate, glaciation), cost, and lack of physical infrastructure (e.g., manpower, electricity). In these situations, seismologists are forced to use existing resources to study the sequence.

The 2008 Strofjorden aftershock sequence occurred off Spitsbergen's southeast coastline. Its remote location, polar environment, and lack of physical infrastructure limited the deployment of temporary seismometers. As a result, only the permanent stations in the region were used to study its evolution. The sequence was triggered by an M_w 6.2 earthquake that occurred off the Svalbard's southeastern coast on February 21, 2008. Over the last five years, it has generated thousands of aftershocks; several have exceeded M_w 4.0. Figure 1 shows the locations (in green) of sequence events published in NORSAR's analyst reviewed regional bulletin.

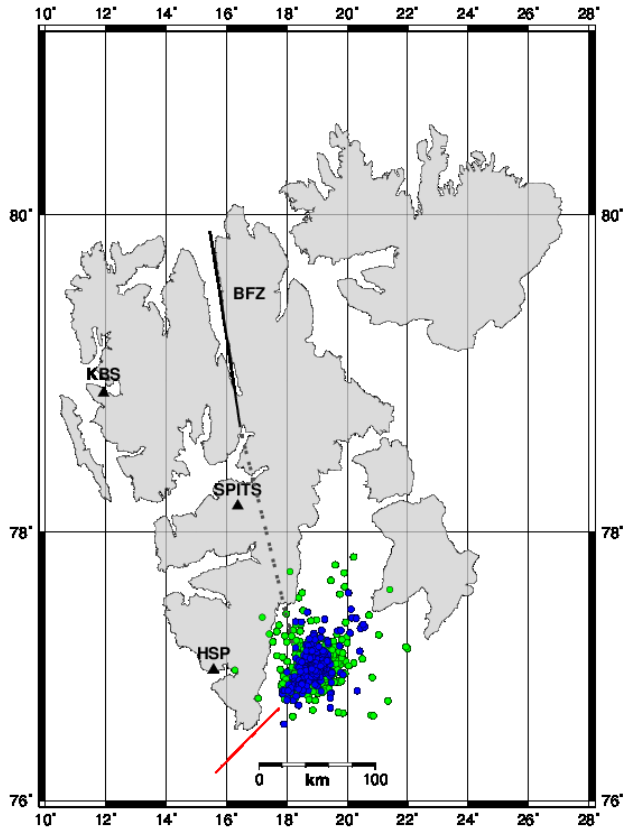


Fig. 1: The Storfjorden aftershock sequence occurred off Spitsbergen's southeast coast. Events shown in green represent the NORSAR analyst reviewed catalog between 21 February 2008 and 20 April 2012. Blue events represent the relocation catalog [11]. The red line shows the location of the shear zone suggested by [1], believed to be related with the Storfjorden sequence [11]. Black triangles show the locations of some of the permanent seismic stations on Spitsbergen. The solid black line shows the location of the Billefjorden fault zone and the black dotted line is its hypothetical extension into the fjord.

Investigations of the regional seismotectonics concluded the source of the sequence was not related to the nearby Billefjorden fault zone (BFZ). Instead, its source is most likely tied to the Tertiary shear zone shown in red in Figure 1. This conclusion is supported by the orientation of the relative relocation catalog, shown in blue in Figure 1, and the orientations of focal mechanisms for numerous sequence events [11,9]. These studies were largely based on the analysis of manually reviewed events. However, the number of events in the NORSAR analyst reviewed bulletin represent a small fraction of the total number of events produced by the sequence.

In this study, an autonomous event detection and clustering framework is used to expand the Storfjorden sequence dataset. The framework automatically spawns new or updates an existing empirical signal detector (ESD) pool upon the detection of a new signal. It groups detections based on waveform similarity and stores detection association information in a relational database. This allows for the detection of low magnitude events originating from common source types and locations to be grouped into families and tracked over the course of the sequence. The expanded dataset is used to infer information about the tectonic structure within the fjord and to examine the sequence's spatiotemporal properties.

2 Signal and Data Processing Methods

An ESD is a generic term that encapsulates many types of multichannel matched filters, which include: array-based correlation, array signal subspace, and signal channel correlation detectors. Numerous studies have demonstrated the power of ESDs for detecting seismic events and measuring their similarity [4,2,12,14]. They are capable of detecting low signal-to-noise ratio (SNR) signals that are originating from a common source type and location, which are difficult for conventional power detectors (e.g., STA/LTA) to identify.

The framework is a java based application that was developed as a collaborative effort between Lawrence Livermore National Laboratory and NORSAR. A block diagram highlighting the framework's core functionality is shown in Figure 2 and a complete decription of an early version of the system is provided in [5]. The framework uses power (STA/LTA) detectors operating on array beams to detect events with new waveform patterns, and automatically spawns correlation detectors to search for additional occurrences of events with those patterns. The framework maintains a pool of such empirically-derived correlation detectors, which may be updated upon the detection of new signals approximately matching the patterns. It groups signal detections based on waveform similarity and stores event affiliation information in a relational database. All framework detections are tagged with an identification number (detector ID) that represents new or previously observed signal types. The database can be mined to study the various aspects of the sequence. For example, detector IDs can be grouped and associated detections counted to identify event clusters. Processing can be initiated using stored detectors and reconfigured to use a lower detection threshold. This allows waveform templates built during later periods of the sequence to be applied to earlier portions of the sequence. Typically this results in the detection of many low SNR signals that were missed in the initial pass.

Event size is estimated using a relative magnitude (mb_{rel}) relationship that scales newly detected events against a user

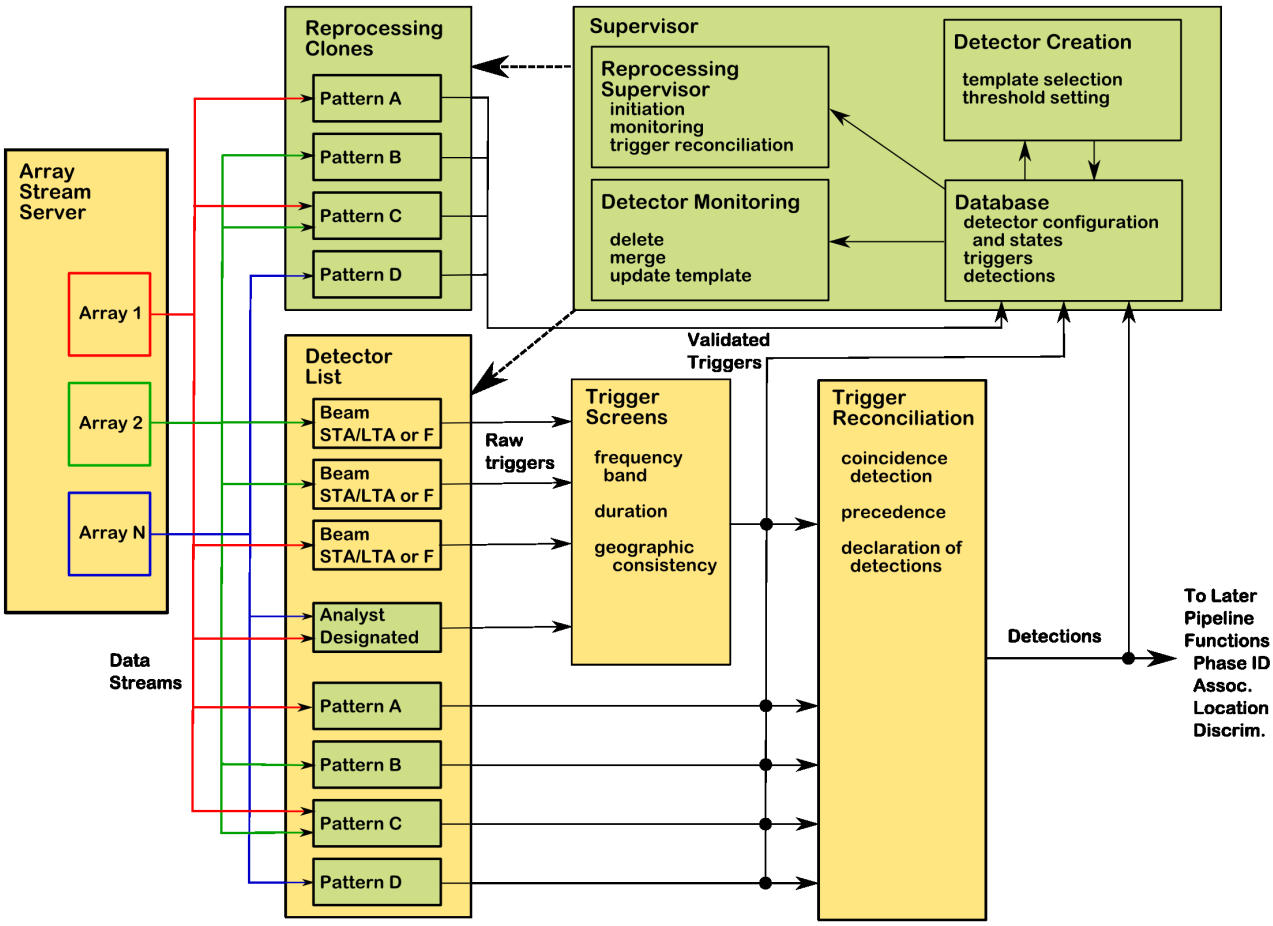


Fig. 2: Autonomous seismic detection and event grouping framework block diagram [5]

defined master event [7]. The relative scaling relationship used in this study is defined as

$$mb_{rel} = mb_r + log_{10}\left(\frac{A_n}{A_r}\right) \tag{1}$$

where mb_r is the reference event bodywave magnitude, A_r is peak amplitude of the reference event seismogram, and A_n is the peak amplitude of the new event seismogram. The reference magnitude is adjusted based on the value of the log amplitude ratio. For example, if the A_n is larger than A_r, then mb_r will be increased by the value of the positive log ratio. However, if A_n is smaller than A_r, then mb_r will be decreased by the value of the negative log ratio. Since all of the events under consideration are originating from a small area, no distance correction is needed. The relative magnitude scale allows bodywave magnitudes to be calculated for all SPITS ESD detections. Relative magnitude estimates are used to produce a cumulative frequency magnitude distribution (FMD) that quantifies the minimum detection threshold for SPITS relative to the Storfjorden region. Comparisons between the analyst reviewed and framework generated catalogs can be performed to quantify the framework's performance.

Determination of the catalog completeness magnitude (M_c) is conducted using the method outlined in [16]. Their method compares the linear sections of the observed and model FMD between the maximum magnitude and an assumed M_c. The goodness of fit between the modeled and observed FMDs is assessed using

$$R(a, b, M_i) = 100 - \frac{\sum_{M_i}^{M_{max}} |B_i - S|}{\sum_i B_i} 100 \tag{2}$$

where R is the goodness of fit, a and b are the Gutenberg-Richter relationship coefficients, M_i is the completeness magnitude being tested, and B and S are the observed and predicted portions of the distribution for each magnitude bin. [16, 3]. The Gutenber-Richter coefficients are determined using a least-squares regression before the initiation of the M_c

Table 1: Processing parameters employed by detection framework for Storfjorden sequence using SPITS data.

Parameter	Value	Description
$Filter$	Bandpass	3 pole Butterworth filter
F_{lo}	2.0 Hz	Low frequency corner
F_{hi}	8.0 Hz	High frequency corner
TL_{min}	20.0 sec	Minimum template length
TL_{max}	33.0 sec	Maximum template length
$Azimuth$	155.0 deg	Detection beam azimuth
$Velocity$	5.5 km/sec	Beam Velocity
Az_{tol}	$\pm$ 20.0 deg	Azimuth Tolerance
Vel_{tol}	$\pm$ 1.0 km/sec	Velocity Tolerance
T_{AP}	20.0	Array power detector Threshold
T_{ESD}	0.2	ESD threshold

estimation routine. This is an iterative process that tests the validity of many M_c values. Here we chose the M_i value with the largest R as the catalog M_c.

3 Discussion of Results

3.1 Processing Configuration

The detection framework was used to process 7 vertical, broadband, elements of the SPITS array between February 21, 2008 and April 20, 2012. Processing parameter values and descriptions are listed in Table 1. The array power detector threshold was set high so only high quality signals are used as ESD templates. Since our ESDs have a large time bandwidth product and use multiple channels of the array, T_{ESD} was set to 0.2. Frequency-Wavenumber (FK) screening was used to remove detections outside of Storfjorden. Signal duration was used as an additional screening metric. Valid detections had durations that fell between TL_{min} and TL_{max}.

3.2 Detection Statistics

The total number of detections and event clusters produced by the detection framework are listed in Table 2. Here FK screening occurs during post processing via an application that runs outside the detection framework. As a result, all array power detections are used to spawn new correlation detectors regardless of their slowness vector. Since the SPITS array observes seismicity from numerous local, regional, and teleseismic sources, a large number of detectors are formed from sources outside of Storfjorden.

Figures 3 and 4 show FK measurements for all detections made over the four and half year processing interval, where black dots fall within the azimuth, velocity, and FK power (see Section 3) constraints listed in Table 1 and red dots do not. The time series plot shows the ESD are identifying events arriving at numerious azimuth and slowness vectors. The azimuth plot shows detections are typically made along back azimuths of 330, 220, and 150, and 60 degrees. The polar plot shows numerious sources of repeating seismicity near the station. Sources of repeating seismicity include, mining activity, ice quakes, local earthquakes, Mid-Atlantic Ridge earthquakes, and Storfjorden events (shown in black). The large number of off target detections highlights the need for post detection azimuth and slowness screening for automatically generated ESDs.

Table 2: Framework detection results, where Y denotes the application of FK screening and N its absences. The detection field denotes the number of detector triggers and the Event Type field represents the number of unique ESDs depolyed by the ssytem in parallel.

Parameter	FK Screening	Results
Detections	Y	15911
	N	76688
Event Type	Y	2509
	N	5072

Table 3: FK measurements for events shown in Figures 5(a) - 5(d)

Example	Azimuth (deg)	Velocity (km/sec)
Event 1	152.89	5.53
Event 2	122.13	9.29

Table 2 shows the number of framework detections and unique ESDs deployed in parallel by the system over the course of the sequence. Approximately 80% of the detections and 51% of the ESDs were rejected after the screening metrics were applied. Examples of valid and invalid event detections with their corresponding FK spectra are shown in Figures 5(a) - 5(d). Example one is a valid detection whose wavefront arrives at the station on the expected azimuth and slowness vector. Example two is also a valid signal detection whose wavefront arrives at the station on an azimuth and slowness vector that is inconsistent with Storfjorden. As a result, event one is associated to the Storfjorden sequence, while event 2 is rejected and not considered in subsequent analysis.

Figures 6, 7, and 8 show the magnitude distributions and M_c estimates for the framework and NORSAR catalogs. The histogram of framework detections almost completely eclipses the analyst reviewed bulletin. Cumulative FMDs show the two distributions have similar b values and highlights detection threshold differences between the two catalogs. M_c estimates for the framework and NORSAR catalogs with the largest R values are 0.8 and 2.1. The difference in M_c estimates shows the framework is providing a 1.3 magnitude unit improvement in detection capability for Storfjorden events observed by SPITS.

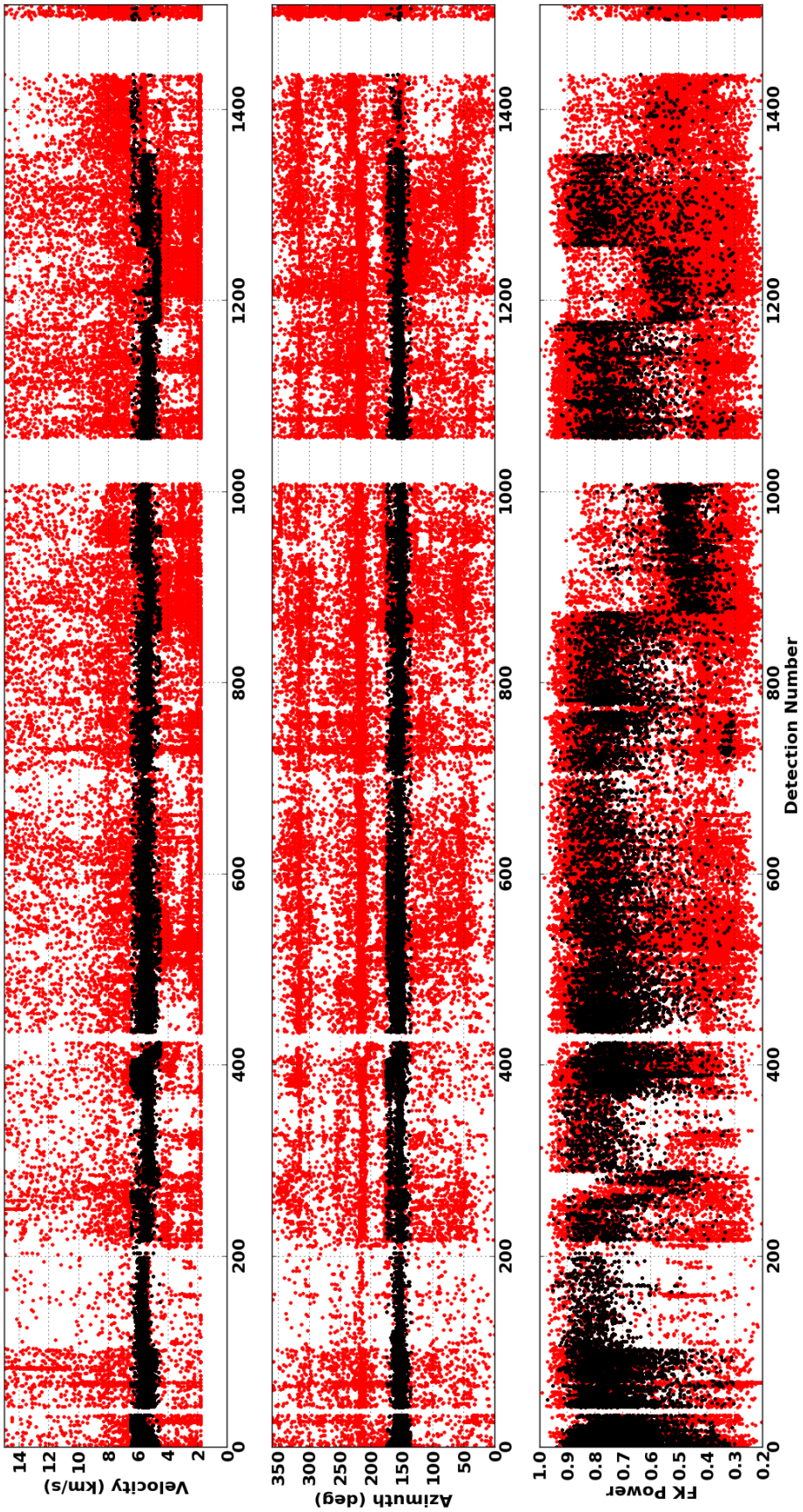


Fig. 3: FK measurements for framework detections, where the top plot is velocity, center is back azimuth, bottom is FK_{pow}, red dots show all detections, and black dots show detections that passed the screening criteria. Gaps in detection processing are observed near days 5, 410, 1010, and 1450.

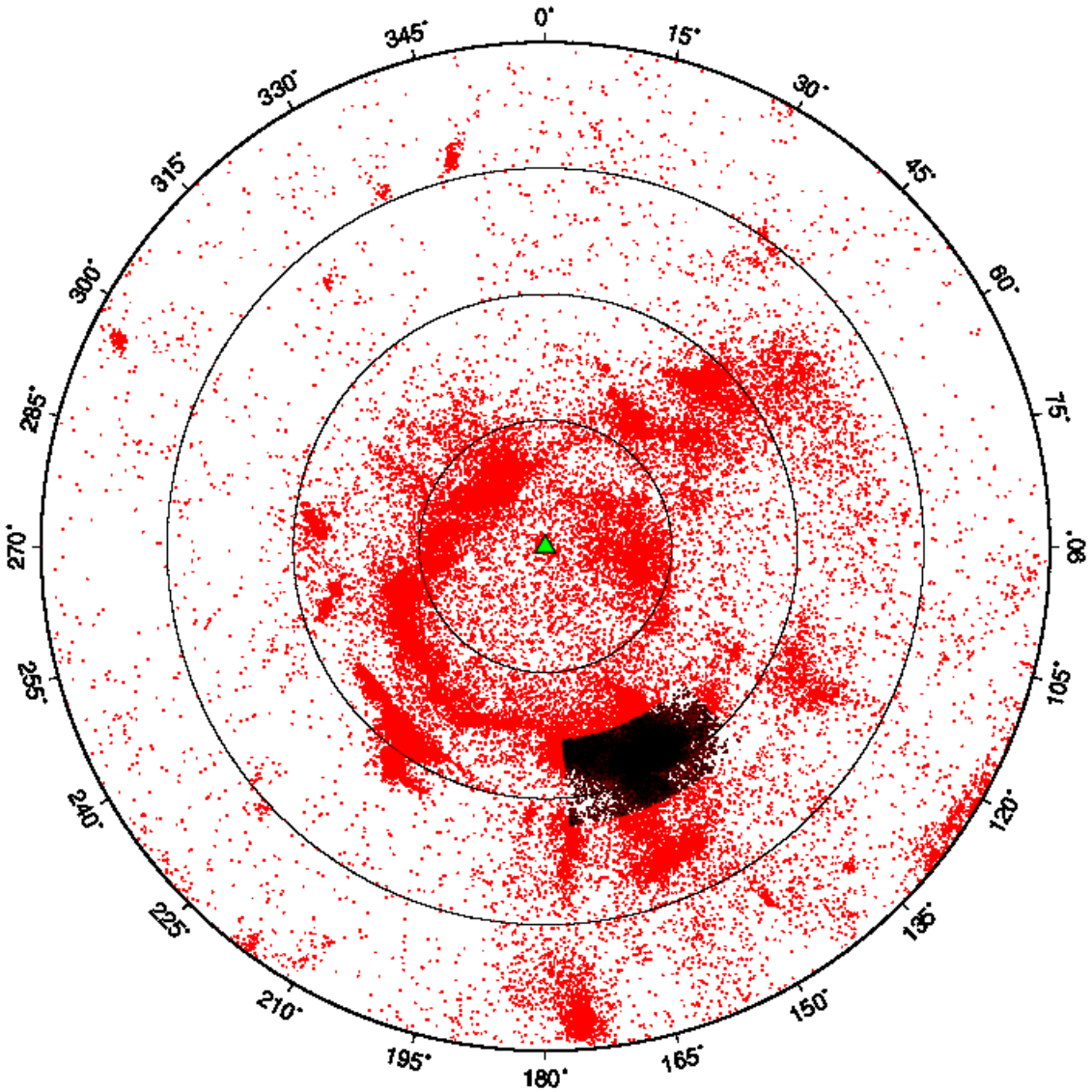
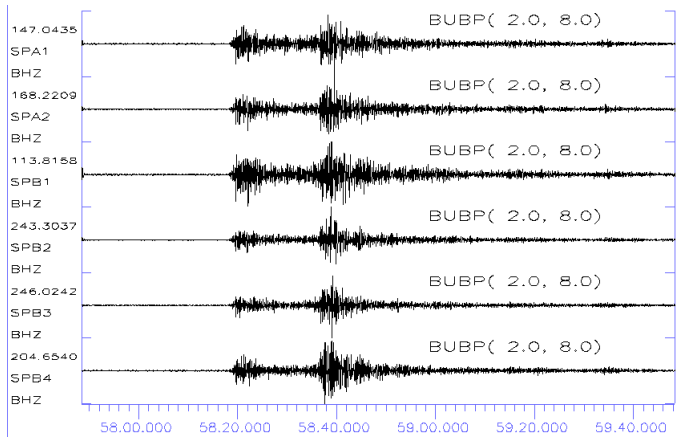


Fig. 4: Azimuth and slowness measurements for all accepted framework detections, where red shows all detections, black are those that passed the FK screening criteria, and the distance between concentric circles is 0.1 sec/km.

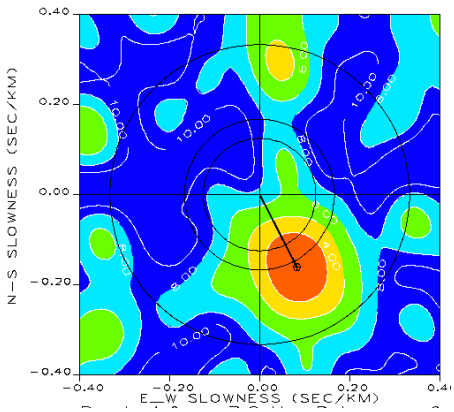
3.3 Space-Time Distribution of Events

Figure 9 shows Pirli's relative relocation catalog and combined moment tensor solutions (from [8,11]) colored as a function of days following the main shock. The figure shows the events are migrating across the rupture zone over time. Magenta events occur during the early stages of the sequence between days 0 and 100. Blue and cyan events tend to occur to the south of the magenta events between days 100 and 800. Green are located to the southeast of the blue and cyan events and occur between days 800 and 1100. Events occurring between days 1100 and 1400 are located to the north of the magenta events. Orange and Red events tend to be located in the central area of the sequence. The moment tensor solutions show a preference for normal faulting along the western flank of the sequence and a mixture of strike-slip and normal faulting along its eastern edge.

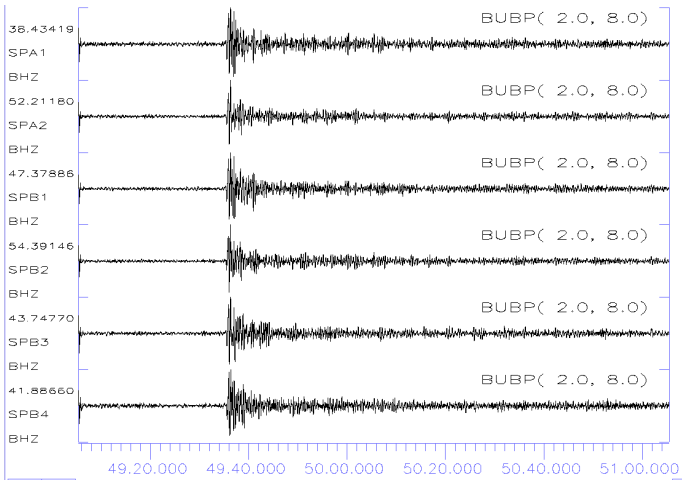
Figures 10(a) and 10(b) show a time series of event detections per day following the main shock for the framework and NORSAR Analyst Reviewed Regional catalogs.



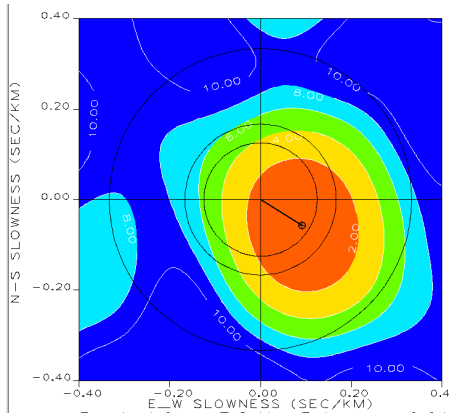
(a) Example 1: Valid signal detection.



(b) Example 1: Correct azimuth and slowness.



(c) Example 2: Valid signal detection.



(d) Example 2: Incorrect azimuth and slowness.

Fig. 5: Examples of ESD detections and corresponding FK measurements for valid and invalid events.

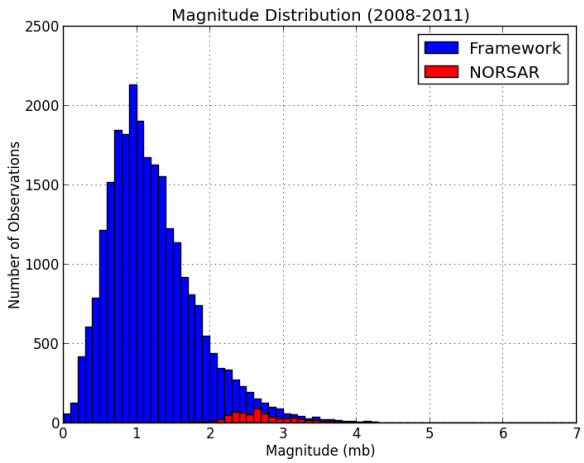


Fig. 6: Binned FMD for framework (blue) and NORSAR (red) catalogs.

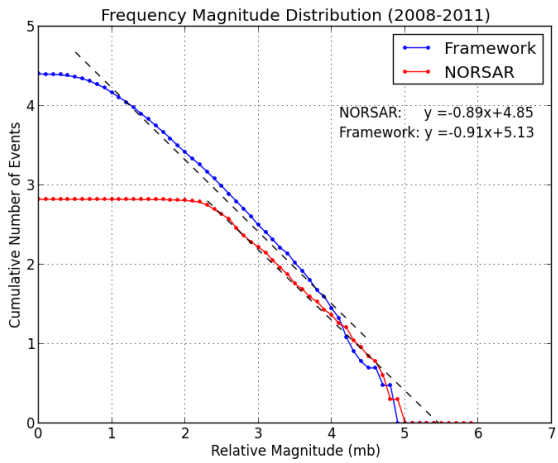


Fig. 7: Cumulative FMD for framework (blue) and NORSAR (Red) catalogs

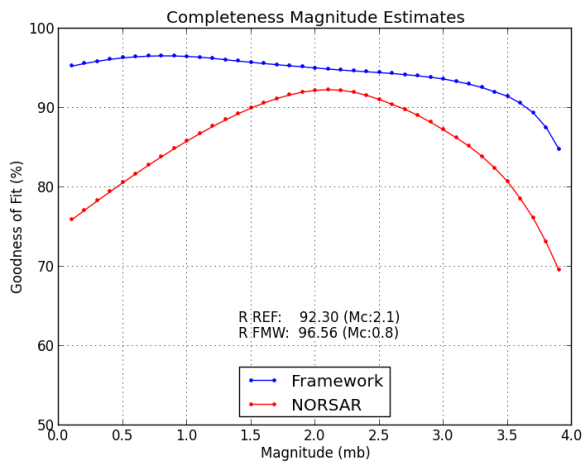


Fig. 8: Goodness of fit measurements for the linear portion of the modeled and observed frequency magnitude distributions for the framework (blue) and NORSAR (red) catalogs.

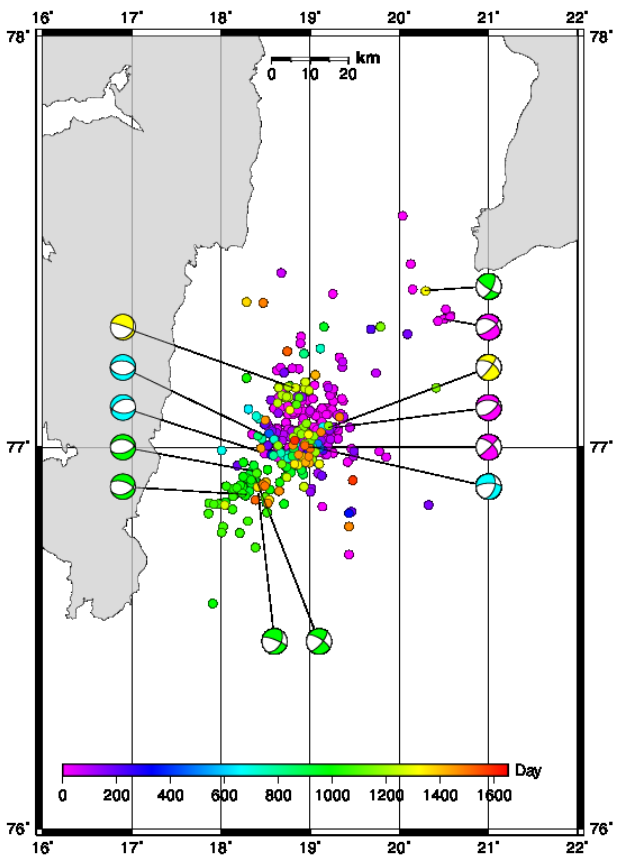
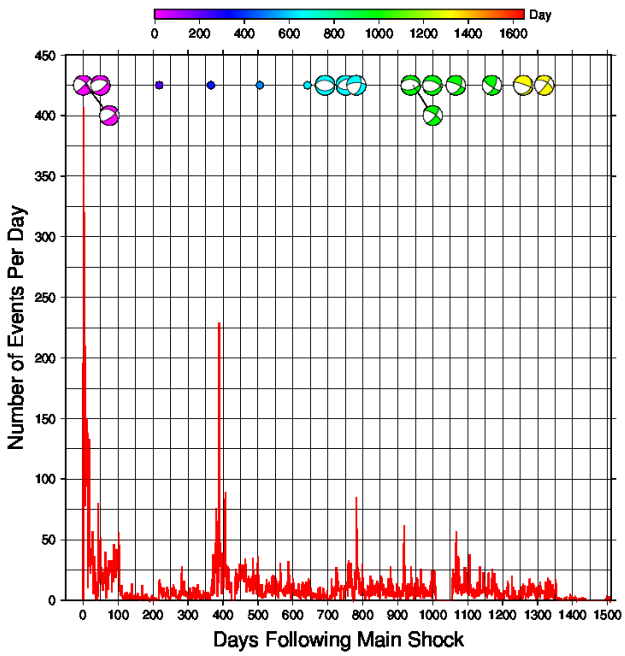
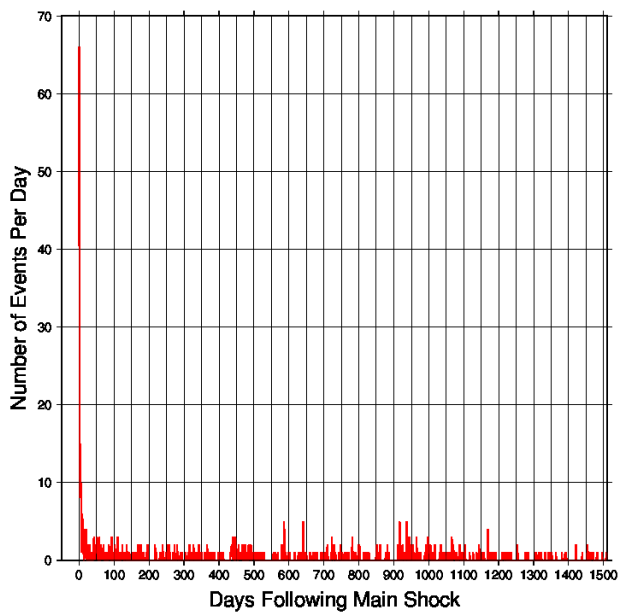


Fig. 9: Relative relocation catalog occurrence time color coded as a function of days following the main shock.



(a) Framework Catalog



(b) NORSAR Analyst Reviewed Regional Catalog

Fig. 10: Detected events per day. a) Framework catalog after applying FK Screening parameters, where focal mechanisms are color coded as a function of days following the main shock. b) NORSAR Analyst Reviewed Regional catalog for Storfjorden.

The occurrence time of events with focal mechanisms or mb_{rel} greater than 4.0 are shown in the top section of Figure 10(a) and are color coded as a function of days following the mainshock. Figure 10(a) shows more events occurring in Storfjorden then documented in the NORSAR Analyst Reviewed Regional catalog. The framework is providing a higher fidelity catalog of events per day, which is highlighting at least eight reactivation episodes (occurring on days 50, 80, 217, 270, 366, 782, 918, and 1066) that are not shown in the analyst reviewed bulletin. Several of these episodes coincide with the occurrence of large events shown in the top portion of Figure 10(a). The results suggest the reactivation episodes are triggered by a larger, preceding, event.

The initiation day, lifespan, and number of members in each event cluster are shown in Figure 11. Lifespan bars indicate the rate of cluster generation is greatest at the beginning of the sequence and remains relatively constant until day 100. At this point, the cluster generation rate decreases and spikes on days where reactivation episodes occur. The lifespan of the clusters vary dramatically, where some last hours and others last the entire length of the sequence. The number of events constituting each cluster also varies significantly. Some groups have a single member, while others have between 10 to 85 members.

Day 100 marks an interesting transition point in the sequence's evolution. Note in Figure 9 that all events occurring prior to day 100 (shown in magenta) are located in the NE section of the sequence. Between days 50 and 100, Figure 10(a) shows the number of events per day are increasing. After day 100, the sequence begins to migrate to the SW, the number of events per day drops below 25, and the cluster generation rate becomes near linear, where its slope (m) is $\approx$ 0.9 clusters/day. One possible explanation for this change in behavior is an asparity failure that allows the stress to propagate to the SW sections of the fault.

3.4 Inferring Tectonic structure

Framework detections were matched to events in the relative relocation catalog based on origin time. After a single event match is found, all occurrences of the event's detector ID in the database are counted and the total represents the number of similar events detected throughout the sequence. All event clusters matched to events in the relative relocation catalog have well defined waveforms, whose S-P times are consistent with Storfjorden events. Selected examples of waveform segments for matched event clusters are shown in Figures 12(a) and 12(b).

Figure 13 shows event clusters with three or more members, relative to all events in the relative relocation catalog. The event activity plot (Figure 13(a)) highlights areas of heightened activity within the sequence. A NE-SW trending linear feature is illuminated by the green, red, blue, and magenta dots in the southeastern portion of the sequence. The orientation of this feature is consistent with the previously mapped shear zone. A dashed black line shows the inferred extension of the shear zone through the sequence rupture zone. Its end point is based on the location of the far northeastern clusters which may be caused by stress build up at the fault termination point. The average and standard deviation of the occurrence time of the events comprising each cluster are shown in Figures 13(b) and 13(c). The most avtive clusters have average occurrence times in the 600 day range and standard deviations of approximately 300 days. Events within these clusters are occurring over the lifetime of the sequence. Figure 14 shows the time distribution of events in the most active cluster (shown in red in Figure 13(a)). Activity within this cluster peaks early in the sequence, decays steadily over the next 650 days, experience moderate reactivation on day 700, and steadily decays again over the remainder of the sequence. This collection of correlated events are most likely produced by a repeating source occuring in approximately the same location. Its temporal distribution suggests that its a miniature aftershock sequence, which is occurring within the larger sequence.

Possible fault systems capable of producing the Storfjorden sequence are shown in Figure 15. The orentation of seismicity in the relative relocation catalog could be produced by a continuous strike-slip fault (see Figure 15a). The large scatter in the relative relocation argues against this simple fault structure and supports deformation distributed over a broader shear zone (see Figure 15b). However, the large scatter in the relocation catalog may be an artifact of the sparse regional network and not the result of distributed tectonic features. The normal mechanisms along the western flank of the sequence suggests there are EW trending features within the NE-SW trending shear zone. The combination of normal and strike-slip mechanisms, along with the relocation catalog orentation, leads us to suggest the en echelon fault structure shown in Figure 15c as a possible source of the sequence. The evolution of the sequence suggests that the rupture (i.e., tear) is initiated by the main shock and propagates to the SW over time.

4 Conclusions

We have demonstrated the use an autonomous event detection and grouping system for studying aftershock sequence properties and inferring tectonic structure in situations where the deployment of temporary sensors is impractical. In this study, the automated system was able to exploit data from a permanent seismic array in the region and improved the catalog M_c by 1.3 magnitude units relative to the NORSAR regional reviewed catalog for Storfjorden.

Processing results generated for the 2008 Storfjorden aftershock sequence identified numerous events that were

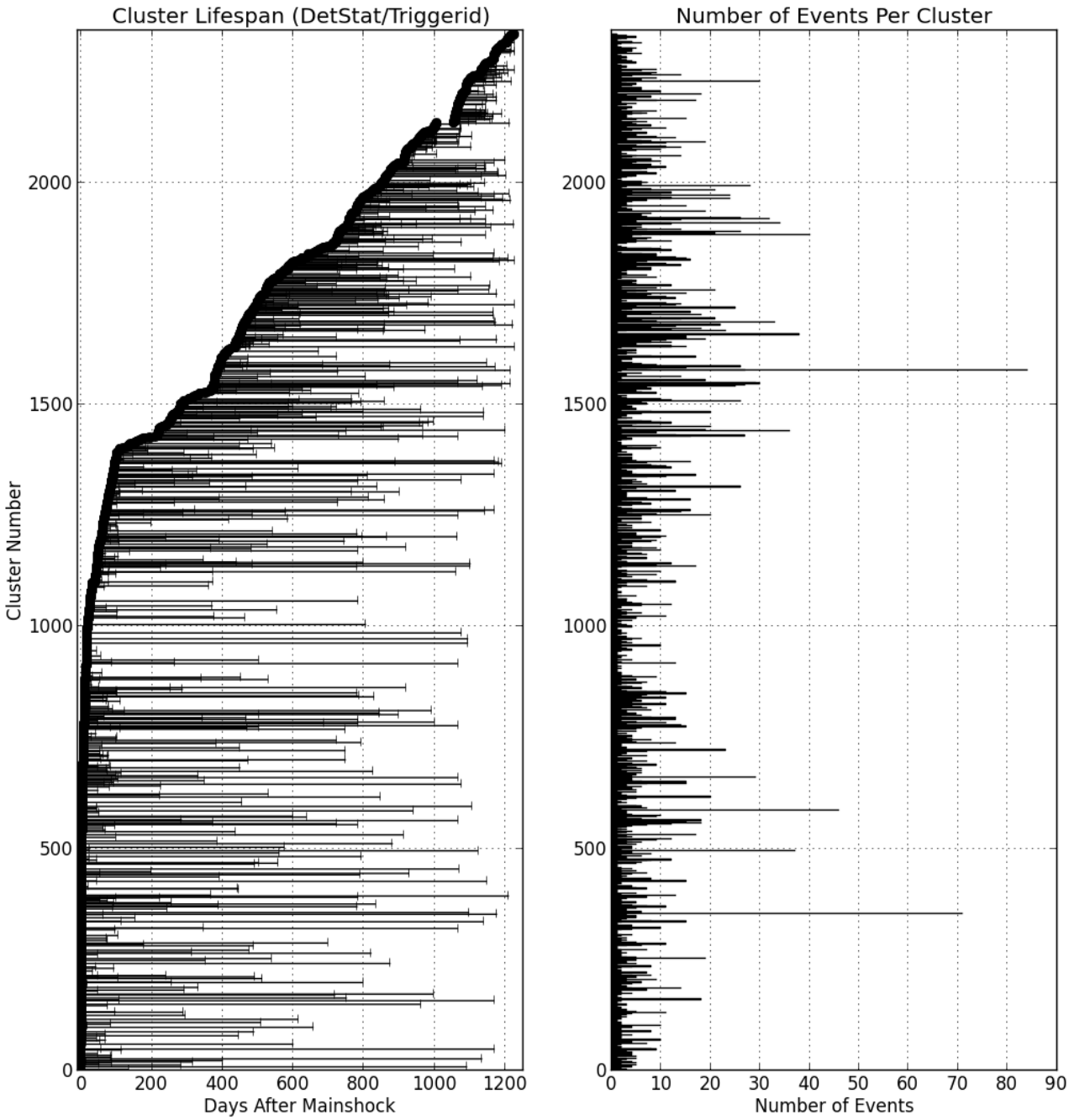
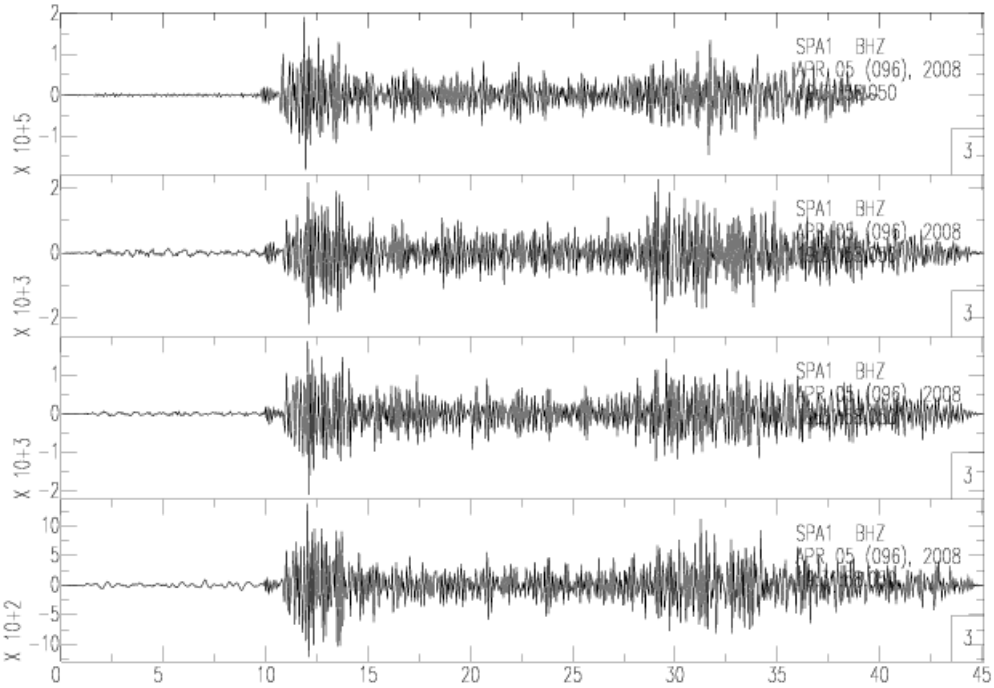
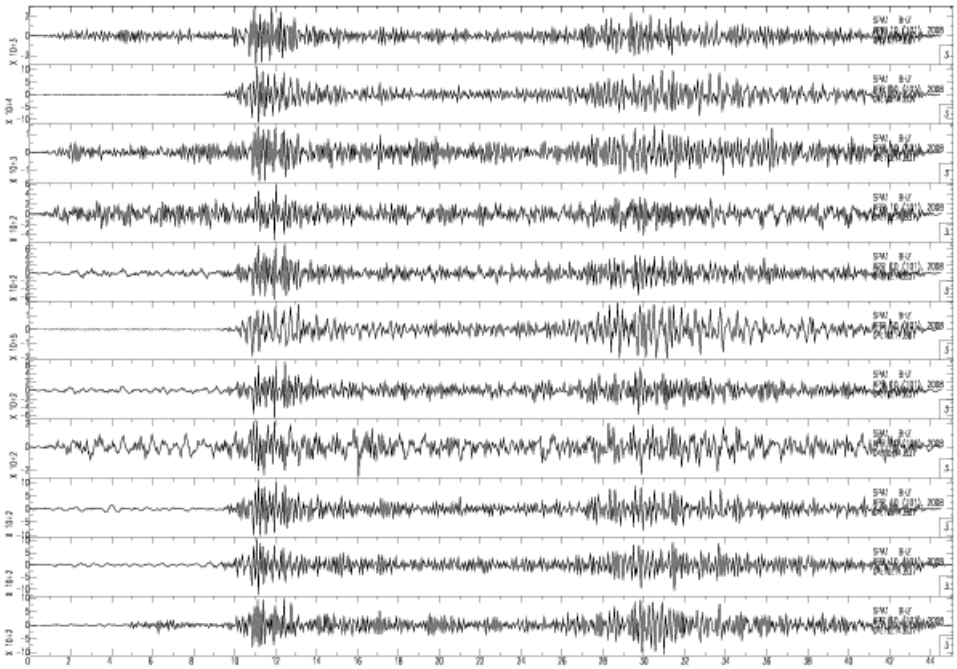


Fig. 11: Cluster lifespan (left panel) and number of events per cluster (right panel), where each point on the lifespan bars represents the initiation time of the cluster.

previously unknown. The results show the sequence is far more complex then the analyst reviewed or relative relocation catalogs suggest. New event clusters with varying duration and number of members are being generated at varying rates throughout the sequence. The spatiotemporal distribution of events is more consistent with an epidemic type aftershock (ETAS) model as opposed to the smooth exponential decay predicted by Omriri's law [10]. The ETAS model suggests aftershocks continuously trigger smaller aftershock sequences over time in a manner similar to the spread of disease epidemics. Our results show that sequence events are triggering episodes of intense activity in different parts of



(a) Example 1

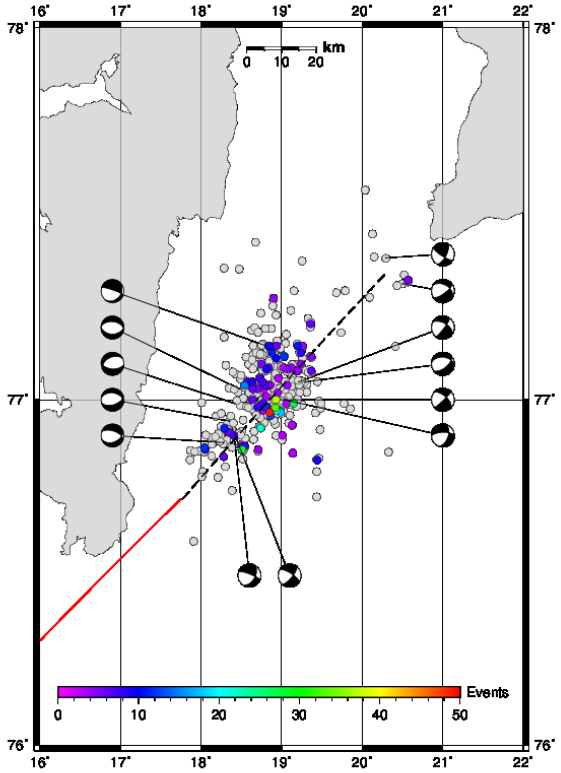


(b) Example 2

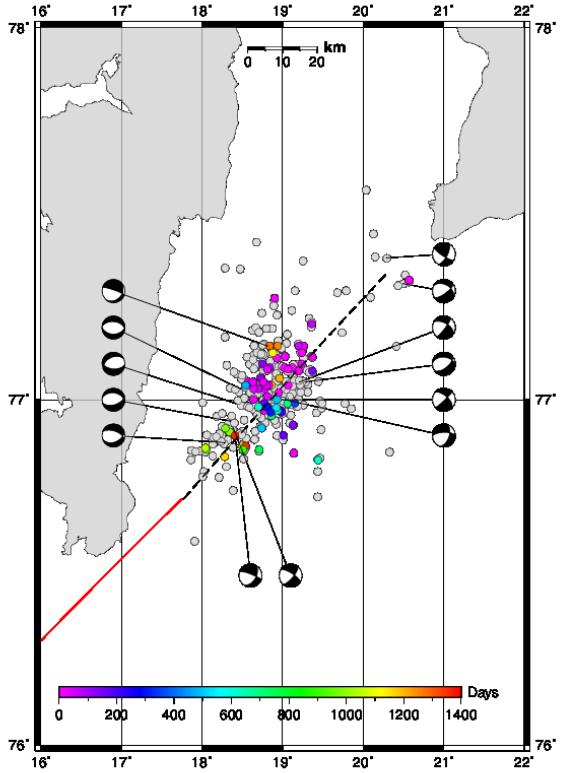
Fig. 12: Examples of event clusters that match an event in the relative relocation catalog.

the fault zone over time. This level of interaction between events is only apparent due to the low detection thresholds of the ESDs. Reactivation episodes are not detected in the analyst reviewed catalog.

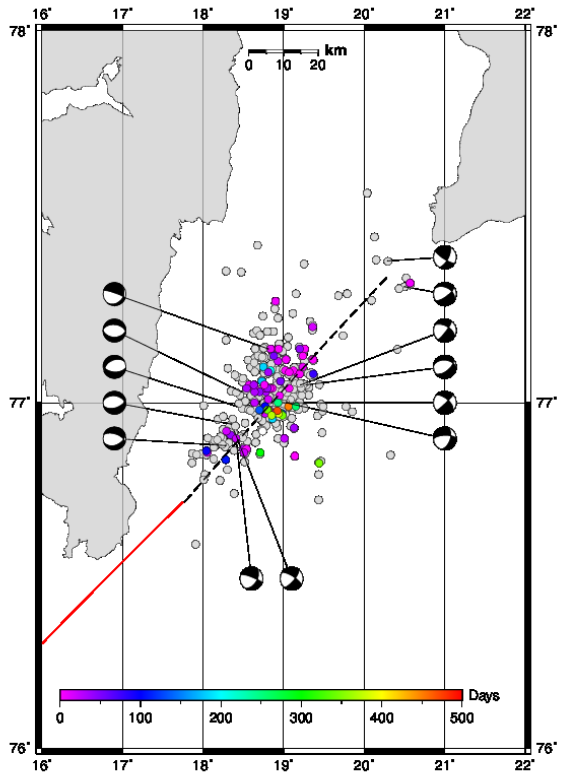
We were able to infer additional information about the tectonic structure within the fjord that was not obvious in the relative relocation and NORSAR analyst reviewed catalogs. Active event clusters were used to highlight areas of elevated activity within the fault zone. This information, combined with the relative relocation catalog, moment tensor solutions, and previously mapped tectonic features, allowed us to infer an extension to the previously mapped Tertiary



(a) Number of events per cluster



(b) Average event occurrence time per cluster



(c) Standard deviation of occurrence time per cluster

Fig. 13: Framework event cluster with more than 3 members matched to events in the relative relocation catalog, where the red line shows the location of the previously mapped Tertiary shear zone and the black dashed line represents the inferred location through the sequence rupture zone. Colored dots represent events clusters that are matched to an event in the relative relocation catalog and gray dots are unmatched events. a) Number of events per cluster. b) Average occurrence time of events per cluster. c) Standard deviation of occurrence time per cluster.

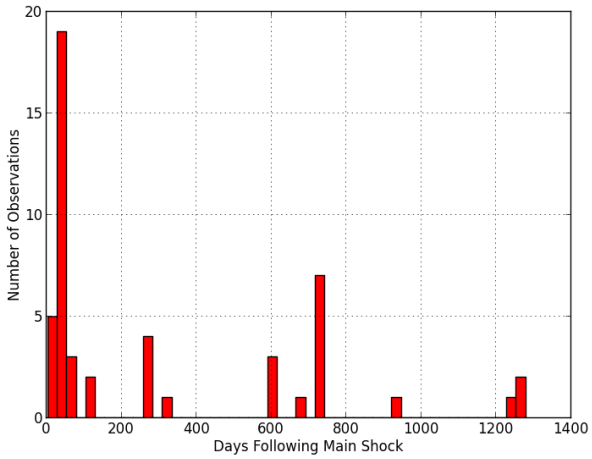


Fig. 14: Number of events per day associated to most active event cluster.

shear zone through the fjord. The proposed NE-SW trending En echelon fault structure supports both the orientation of the relative relocaiton catalog and mixture of strike-slip and normal focal mechanisms.

Future work will focus on the application of ESDs to larger sequences (e.g., 2008 Sichuan sequence) for extending available datasets and inferring tectonic structure. In addition, the framework will be used to study the space-time distribution of selected aftershock sequences to determine their agreement with ETAS models.

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A Definition of FK Power

The FK_{pow} metric is a measure of multichannel coherence (i.e., semblance) and is defined as

$$FK_{pow} = \frac{\sum_{j=k-\frac{1}{2}N}^{k+\frac{1}{2}N} \left[\sum_{i=1}^{M} f_{i,j} \right]^2}{\frac{1}{M} \sum_{j=k-\frac{1}{2}N}^{k+\frac{1}{2}N} \left[\sum_{i=1}^{M} (f_{i,j})^2 \right]} \tag{3}$$

where M is the number of channels, N is the window length, k is the point where the window is centered, and $f_{i,j}$ is the ith sample value of the jth trace [13].

References

1. Bergh, S.G., Grogan, P.: Tertiary structure of the Sorkapp-Hornsund region, South Spitsbergen, and implication for the offshore southern extension of the fold-thrust belt. Norwegian Journal of Geology (83), 43–60 (2003)
2. Gibbons, S.J., Ringdal, F.: The detection of low magnitude seismic events using array-based waveform correlation. Geophysical Journal International **165**(1), 149–166 (2006). DOI 10.1111/j.1365.264X.2006.02865.x
3. Gutenberg, R., Richter, C.F.: Frequency of earthquake in California. Bulletin of the Seismological Society of America **34**, 185–188 (1944)
4. Harris, D.B.: Subspace detectors: Theory. No. ucrl-tr-222758, Lawrence Livermore National Laboratory (2006)
5. Harris, D.B., Dodge, D.A.: An autonomous system for grouping events in a developing aftershock sequence. Bulletin of the Seismological Society of America **101**(2), 763–774 (2011). DOI 10.1785/0120100103
6. Hunter, J.D.: Matplotlib: A 2d graphics environment. Computing In Science & Engineering **9**(3), 90–95 (2007)
7. Junek, W.N., Harris, D.B., Ichinose, G.A., Woods, M.T.: Automated analysis of the Mogul-Somersett earthquake sequence. In: Eos Trans. American Geophysical Union, 89(53), Fall Meeting Supplement, abstract S51C-1756 (2008)
8. Junek, W.N., Roman-Nieves, J., Woods, M.T.: Crustal structure beneath western spitsbergen inferred through joint inversion of teleseismic receiver functions and regional surface wave dispersion. In: American Geophysical Union, Fall Meeting, abstract S31A-2039 (2010)
9. Junek, W.N., Roman-Nieves, J., Woods, M.T.: Tectonic implications of earthquake mechanisms in svalbard. Geophysical Journal International (2014)
10. Ogata, Y.: Statistical models of earthquake occurrences and residual analysis for point processes. Journal of the American Statistical Association **83**(401), 9–27 (1988)
11. Pirli, M., Schweitzer, J., Paulsen, B.: The Storfjorden, Svalbard, 2008-2012 aftershock sequence: Seismotectonics in a polar environment. Tectonophysics (2013)
12. Schaff, D.P., Waldhauser, F.: One magnitude unit reduction in detection threshold by cross correlation applied to Parkfield (California) and China seismicity. Bulletin of the Seismological Society of America **100**(6), 3224–3238 (2010). DOI 10.1785/0120100042
13. Sheriff, R.E.: Encyclopedic Dictionary of Exploration Geophysics. Society of Exploration Geophysicists (1973)
14. Slinkard, M.E., Carr, D.B., Young, C.J.: Applying waveform correlation to three aftershock sequences. Bulletin of the Seismological Society of America **103**(2A), 675–693 (2013). DOI 10.1785/0120120058
15. Wessel, S., Smith, W.: New, improved version of the generic mapping tool released. EOS Transactions AGU **79**, 579 (1998)
16. Wiemer, S., Wyss, M.: Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the Western United States, Japan. Bulletin of the Seismological Society of America **90**(4), 859–869 (2000)

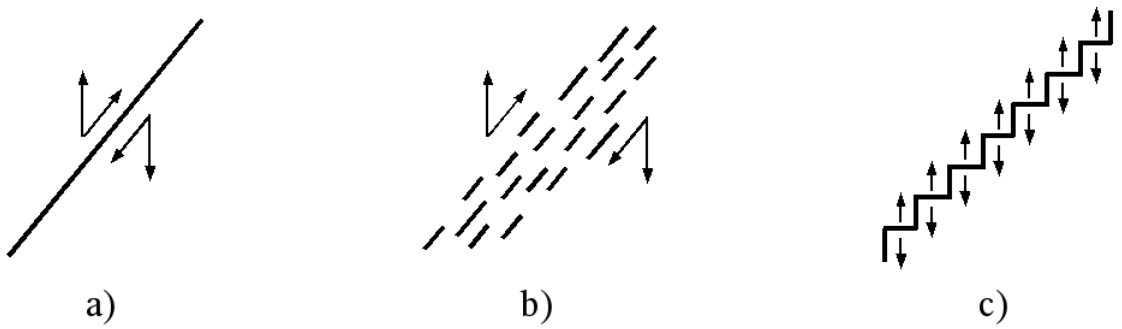

Fig. 15: Possible fault structures which could produce the Storfjorden sequence, where the en echelon structure is capable of producing the spatial distribution of events observed in the relative relocation catalog and both strike-slip and normal focal mechanisms. a) Continuous strike-slip fault. b) Deformation distributed over a broader shear zone. c) En echelon fault.

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