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6.3 Locating seismic events near the Spitsbergen archipelago

Introduction

The work described in this paper is a part of KRSC - NORSAR cooperative activity aimed at a detailed study of seismicity in the Spitsbergen region. Part of the motivation for the study is to improve the quality and availability of well-located reference events ("ground truth data") for location calibration purposes, and to improve automatic and interactive event location accuracy.

Spitsbergen and the adjacent areas are parts of a geologically complex region with moderate to high seismicity. The main seismicity in the area is associated with the North-Atlantic Ridge, and especially the Knipovich Ridge situated at a distance less than 400 km from the archipelago (Sundvor and Eldholm, 1979, Bungum et. al., 1982, Mitchell et. al., 1990). In addition, some coal mines are located in the area of Spitsbergen, causing occasional induced seismicity. In this study we describe some of our observations of unusual features of seismic events and seismic wave propagation in the area and illustrate some problems in event location by comparing various earthquake bulletins.

Seismicity of the Spitsbergen region

The local earthquake activity on Spitsbergen and in adjacent seas is significant. Larger earthquakes are reported by the Norwegian National Seismic Network, and are routinely included in international seismic bulletins. However, until recently there has not existed any systematic and detailed monitoring of the smaller seismic events that often occur in mining areas.

Studies related to the earthquake activity on Svalbard and in adjacent seas have been presented in several previous NORSAR Semiannual Technical Summaries, e.g. Asming et. al. (1998, 2002), Kremenetskaya et al. (2001b), Kværna et. al. (2003). Active earthquake zones are found on Heerland and on Nordaustlandet. In addition, there is significant earthquake activity on the Mid-Atlantic Ridge about 100-200 km west of Vest-Spitsbergen.The Western Barents Sea south of Svalbard also exhibits frequent earthquake activity, and on 4 July 2003, a m_b of 5.4 earthquake with several aftershocks occurred in this region.

A general picture of seismic activity in Spitsbergen and adjacent areas still remains unclear due to several reasons such as small number of stations registering most part of local earthquakes, unknown travel time model for the region, and complex pattern of seismic waves arrivals due to complexity of the conductive medium.

Relocating Spitsbergen earthquakes

We made an attempt to relocate manually a set of earthquakes occurred in Spitsbergen during the first half of 2003. Our goal was to clear up spatial distribution of the events to try to find some characteristic features.

We selected more than 200 events which were strong enough to be registered by at least two stations: Kings Bay (KBS) and the Spitsbergen array (SPITS). For some of them ARCES data were also used. We used the SPITS0 travel time model (Asming et. al., 2002) which is reproduced in Table 6.3.1. This is a one-dimensional model which differs from our basic BARENTS model (Kremenetskaya et. al., 2001a) by including a top layer with low velocities representing sediments. During the data analysis we noticed several specific features of the waveforms which cause difficulties in the event location procedure. One of them is multiple arrivals of P and S waves. The situation is typical for events occurring in the North-East land and to the south and south-east of Spitsbergen.

Table 6.3.1. Velocity model SPITS0

Depth (km)	Vp (km/s)	Vs (km/s)
0-2	4.54	2.52
2-10	6.20	3.44
10-30	6.70	3.72
30-55	8.10	4.50
55-210	8.23	4.57
>210	Same as IASPEI 91	

The complexity of the geological structure and underwater topography causes difficulties in location and interpretation of seismic events. We will present some examples in the next section.

Examples of recordings

Figure 6.3.1 shows a recording by the broad-band station KBS of a relatively strong earthquake in the North-East land during 2003 (ML=2.2). Two arrivals of both P-waves (P1, P2) and S-waves (S1,S2) are seen, the amplitudes of the first arrivals are much smaller than for the second arrivals. The same situation is seen for other earthquakes in this area. In general, the first arrival of S (S1) can be found only for the strongest events. For smaller events this arrival is masked by the P-wave coda. For still weaker events even the phase P1 becomes undetectable. Thus, typical mistakes when locating such events are to make wrong association of P and S phases, e.g. P1-S2 and P2-S2 instead of P1-S1. This can lead to distance errors of typically 50 km for events from this region.

We can correct this problem if we assume that the pattern of P and S phases are consistent for all events in this particular region. For example, if two P-phases and one S-phase are detected (the most common situation), we can assume that the S-phase is S2, and infer the approximate arrival of the first S-phase. In this way, it is usually possible for the analyst to find the S1 phase and use it in the location procedure. An alternative would be to develop a set of travel time curves for the P2 and S2 phases as well as for P1 and S1, but this approach has not been attempted. In any case, picking the correct phase arrival times for such complicated recordings is difficult, and the analyst needs to take into account detailed region-specific information on the waveform characteristics in order to make the correct pick.

A second example of an earthquake in the same area is shown in Figure 6.3.2. The same pattern of P and S phases is observed (P1, P2, S1, S2), but in addition there is also evidence of a possible Lg phase. Again, the interpretation and phase picking of such traces are quite difficult even for an experienced analyst.

For earthquakes occurring in the mid-Atlantic ridge zone, multiple arrivals are likewise observed. As an example, Figure 6.3.3 shows SPITS recording of a small earthquake in this area. In this case, three phases with estimated P-type velocity are observed, followed by a single S-phase. Here it is possible to use the phase velocity measurements by the array to identify the phases, but for single (3-component) stations, the seismogram interpretation will be ambiguous. For example, the phase P3 may easily be interpreted as Sn and the S-phase could then be interpreted as Lg.

To some extent, the phase picking is simplified if a network of seismic stations at different azimuths is available. In the case of Spitsbergen, many of the larger events (magnitude 2 and above) are observed by the ARCES array, and this helps remove ambiguities in the phase picking. Nevertheless, most small earthquakes are detected only by SPITS and (in some cases) by the nearby KBS station, and the events must therefore be located without the benefit of network observations.

While array velocity estimates are helpful in phase identification, we must also note that the estimated phase velocities for events near Spitsbergen often show significant anomalies. For example, many events in the rift zone have almost identical phase velocities for P and S phases. A possible explanation could be P to S conversion near the SPITS array. For other azimuths, the P and S phase velocities are close to normal.

A location experiment

As earlier mentioned, we have relocated more than 200 earthquakes occurring during the first half of 2003 with epicenters in Spitsbergen and adjacent areas. All of these events were detected by at least two stations (usually KBS and SPITS, sometimes with addition of ARCES and other distant stations). We compared our location results with those published in the Reviewed NORSAR Regional Bulletin, which makes use of the same station network. Additionally, we compared both of these interactive location results to the automatic location provided by the on-line GBF procedure at NORSAR.

We note that the GBF procedure uses only the regional arrays in the on-line process; therefore, the KBS station is not included in the GBF processing. However, since GBF accepts epicenters with only single-array detections (P and S), all of the events in the data set (a total of 207) had GBF solutions. We would of course expect the reviewed solutions to be more accurate than the automatic solutions, especially since KBS is not included in the automatic process, but it is nevertheless instructive to compare these procedures. We also note that the NORSAR Reviewed bulletin contained 75 of the 207 events, so the database for comparing this bulletin to KRSC and GBF was more limited.

Most of the earthquakes in this database are very small, usually in the magnitude range 1.0-2.0, and sometimes below 1.0. Clearly, obtaining accurate locations of such small events using a sparse network of stations is difficult, and one can expect significant uncertainties, as will be illustrated in the following.

The results of the location experiment are summarized on the maps in Figures 6.3.4 through 6.3.6, with histograms of the location differences shown in Figure 6.3.7. Our comments to these results are summarized as follows:

Comparing reviewed location results (NORSAR vs. KRSC)

From Figure 6.3.4 we note that the two sets of analyst reviewed locations (NORSAR and KRSC) in general are quite consistent. However, we note a systematic shift in the locations of groups of events, with the KRSC locations generally being shifted in westernly directions compared to those of the NORSAR analyst. Mostly, the location differences are small (a few tens of kilometers), but for a few events the difference exceeds 100 km, and in one case it is more than 200 km. The smaller differences can be attributed, at least in part, to the different velocity models used at KRSC and NORSAR (KRSC uses the SPITS0 model, whereas NORSAR uses a general Fennoscandian model). The cases with large differences are a direct consequence of the difficulties in phase interpretations discussed earlier, and demonstrates that locations of small earthquakes in this region can be associated with significant uncertainties.

Comparing automatic and reviewed location results

Figure 6.3.5 compares the NORSAR analyst reviewed locations to those generated by the automatic GBF procedure. We note that the analyst reviewed locations are more systematically located in the known seismic areas (the mid-Atlantic ridge and some concentrated earthquake zones in the North-East Land and South of the Spitsbergen archipelago). Nevertheless, the automatic GBF locations are typically quite good for this data set, which comprises the larger events in the database.

Figure 6.3.6 compares the KRSC reviewed locations to those generated by the automatic GBF procedure. Again, we note that the reviewed locations are more systematically located in the known seismic areas, but in this case the shifts in locations relative to the automatic procedure are larger than was observed for Figure 6.3.5. Part of the reason is that this data set contains many more small events than that presented in the previous figure, and these small events are usually less accurately located by the automatic procedure (using single-array locations only). In addition, the KRSC procedure, as earlier described, attempts to resolve ambiguities in cases of multiple phase detections, and this can have a significant effect on the resulting locations.

Conclusions

The geology of the Spitsbergen archipelago and surrounding regions is complex, and results in very complex seismograms from some areas. Multiple onsets of P and S waves can strongly increase location errors. Such onsets are not uncommon for Spitsbergen earthquakes.

By studying a set of more than 200 earthquakes in this region, we have shown that analyst reviewed locations (as processed by different analysts) can have occasional large deviations, in several cases exceeding 100 km.

The automatic GBF locations produced on-line at NORSAR are usually quite consistent with the analyst reviewed solutions, but the differences in locations can be large for the smaller earthquakes, which are located using the SPITS array alone in the GBF procedure.

Future work should focus on making more systematic use of array azimuth estimates for small events, perhaps by introducing fixed-frequency f-k analysis (Kværna and Ringdal, 1986) both in the automatic and interactive procedures. With the upgrade of the SPITS array in the near future, attention should also be given to high-frequency processing of data for phase identification and velocity/azimuth estimation purposes. Furthermore, the planned installation of several three-component seismometers in the upgraded SPITS array is expected to significantly improve the automatic S-wave detection capability, thereby improving the ability to locate small seismic events in the region.

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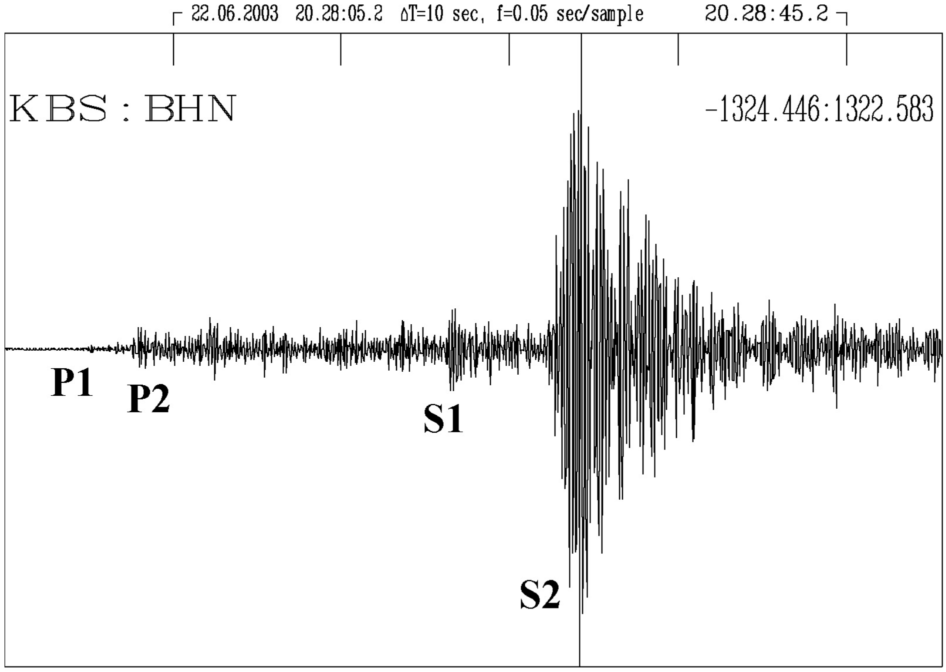

Fig. 6.3.1. *KBS (broad-band N/S) recordings of earthquake in the North-East land. The trace has been high-pass filtered above 4 Hz.*

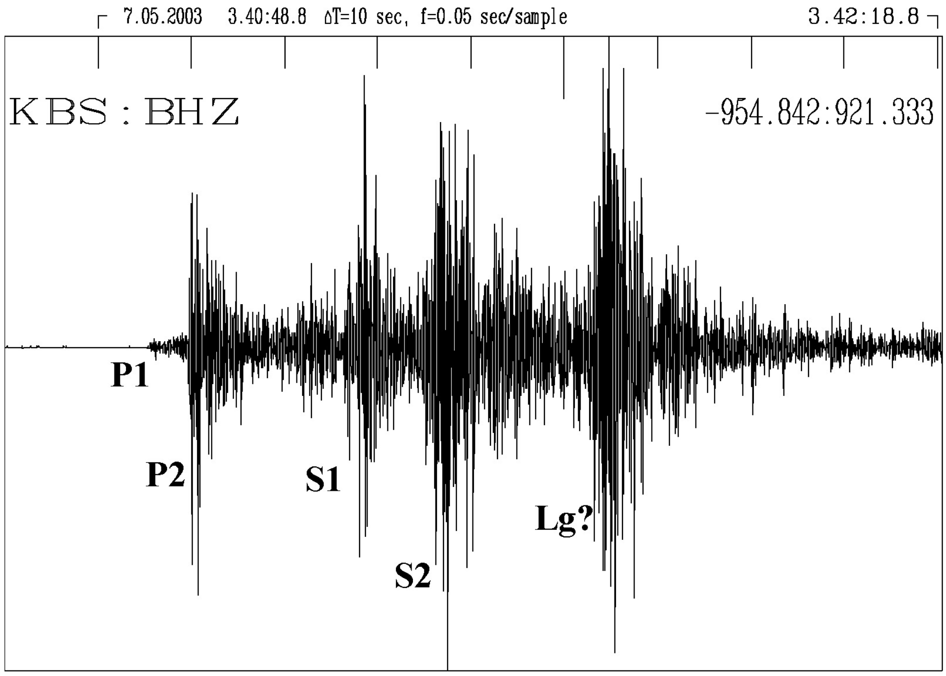

Fig. 6.3.2. *KBS (broad-band vertical) recordings of earthquake in the North-East land. The trace has been high-pass filtered above 4 Hz.*

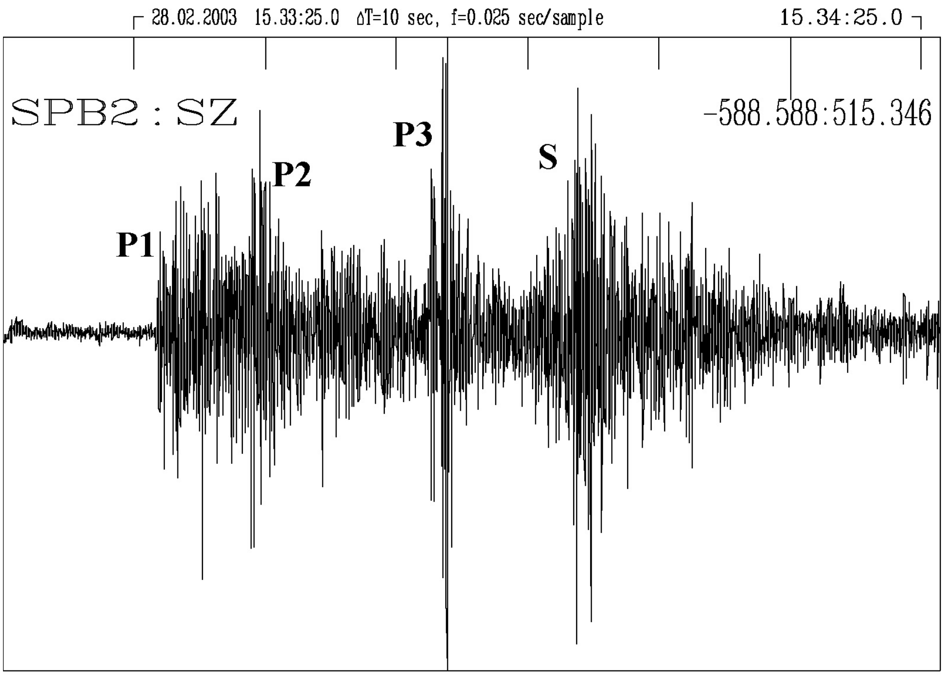

Fig. 6.3.3. *SPITS recordings of earthquake in the rift zone. At least three P-arrivals can be seen. The trace has been high-pass filtered above 4 Hz.*

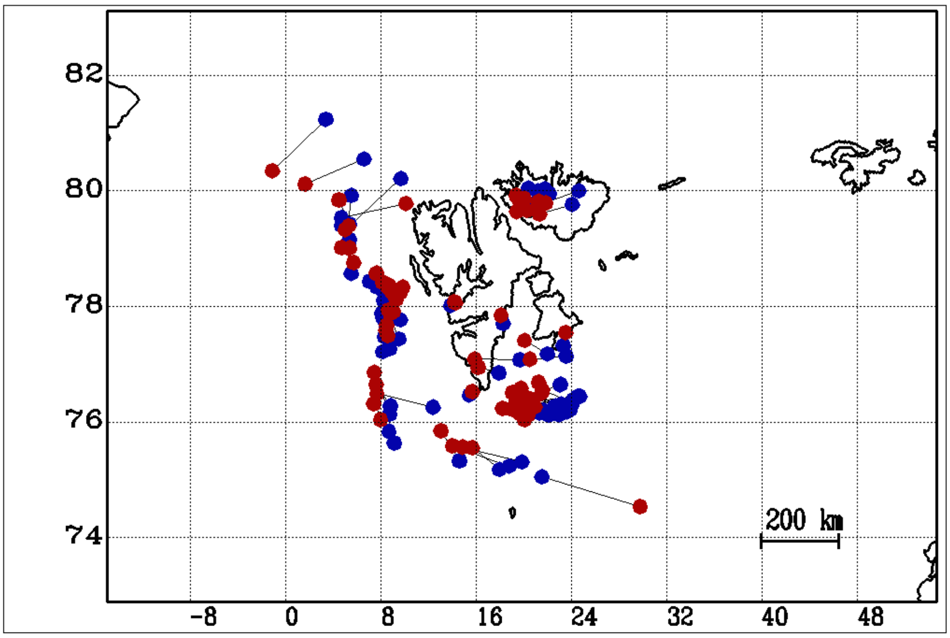

Fig. 6.3.4. *Location comparison: KRSC (red) vs. NORSAR reviewed bulletin (blue)*

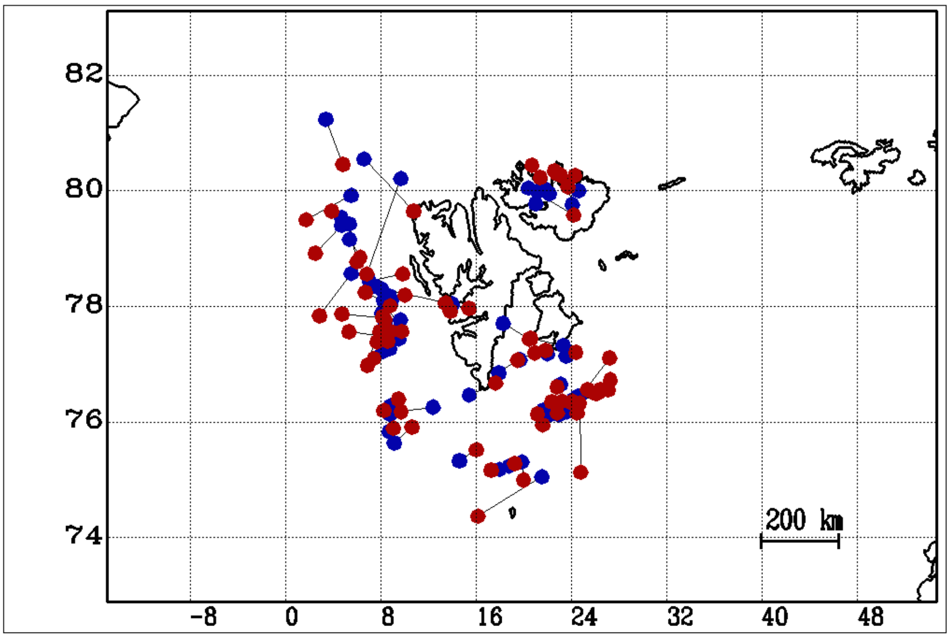

Fig. 6.3.5. *Location comparison: NORSAR automatic GBF (red) vs. NORSAR reviewed bulletin (blue)*

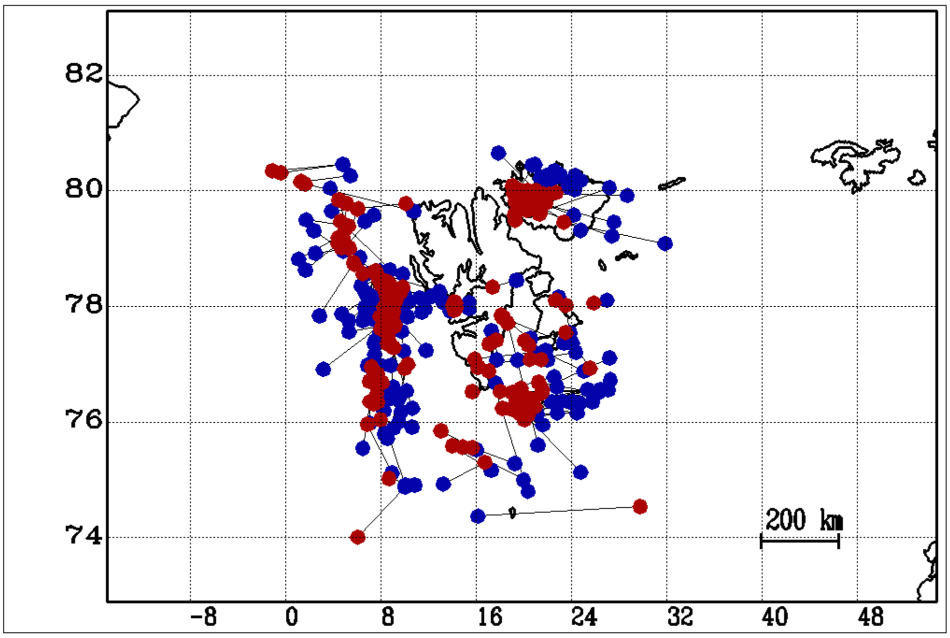

Fig. 6.3.6. *Location comparison: KRSC (red) vs. NORSAR automatic GBF (blue)*

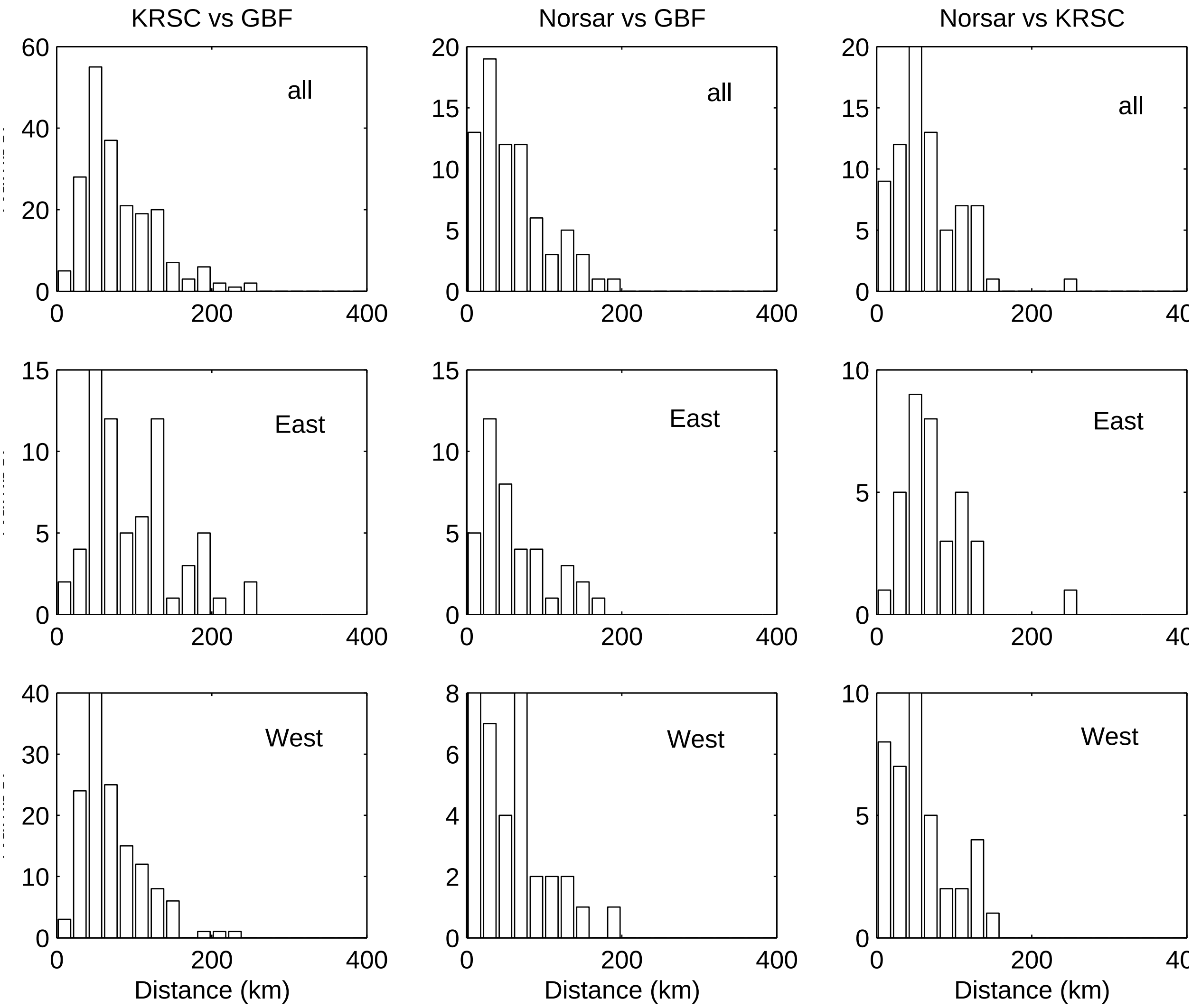

Fig. 6.3.7. *Location comparison between a) KRSC interactive location (KRSC), b) NORSAR reviewed regional bulletin (Norsar) and c) the NORSAR automatic Generalized Beamforming (GBF). The top row comprises all events, the middle row corresponds to events located by KRSC to the East of 16 degrees longitude, and the bottom row represents events to the West of this longitude.*