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7.3 Intelligent post-processing of seismic events -- Part 3: Precise relocation of events in a known target region

Introduction

From experience with analyst review of events automatically defined by the Intelligent Monitoring System (IMS) (Bache et al, 1993), we have realized that the quality of the automatic event locations can be significantly improved if the event intervals are reprocessed with signal processing parameters tuned to phases from events in the given region. The tuned processing parameters are obtained from off-line analysis of events located in the region of interest. The primary goal of such intelligent post-processing is to provide event definitions of a quality that minimizes the need for subsequent analysis and review.

In this third paper on intelligent post-processing of seismic events we test an event location method that makes use of accurate retiming of seismic phases and accurate re-estimates of azimuth using broad-band analysis of array data. The key to obtaining such accurate estimates is the knowledge, provided by the IMS, of an approximate event location in a known area with good calibration information. Various aspects of generalizing the method and incorporating it into the IMS are also discussed.

Location of regional events

Seismic event location has traditionally relied upon P-wave arrival times from a large number of stations. For small events observed only at regional distances, it has been necessary to include arrival times of later phases as well as arrival azimuths in order to obtain acceptable location accuracy (Bratt and Bache, 1988; Thurber et al, 1989). With a sparse network, the number of arrival time observations may often be so low that azimuth information is given considerable weight in the location scheme. However, as the number of observations increases, the relative importance of the azimuths decreases sharply, in view of the generally large uncertainties (10 degrees or more) that are associated with azimuth estimates (e.g., Suteau-Henson, 1990; Bame et al, 1990).

Kværna and Ringdal (1986) demonstrated that the uncertainty of azimuth estimates from regional arrays can be greatly reduced by applying a broad-band estimation scheme in which the frequency band is kept constant for a given epicentral region. Thus, for NORESS observations from Blåsjø explosions (distance 300 km) with high SNR, they found an azimuth standard deviation of only 1.0 degrees for Pn phases and 1.5 degrees for Sn and Lg phases.

This observation suggests that given an initial (approximate) event epicenter, it should be feasible to determine an optimum frequency band (based upon previous observations) and apply broad-band F-k analysis in order to obtain very accurate azimuth estimates, which can then be used to refine the event location. The basic idea of this paper is to establish and test a method for location refinement which takes into account both the stable azimuth estimates obtained by fixed frequency broad-band analysis and the accurate timing observations described in Section 7.2. We use as an example IMS-reported events in the Khibiny Massif recorded by the nearby Apatity array and the more distant ARCESS array. We show that a significant improvement can be obtained relative to the current IMS processing. Moreover, the method is completely automatic and can easily be incorporated into the IMS, as illustrated in Fig. 7.3.1.

As shown in Section 7.1, the majority of seismic events in Fennoscandia can be associated with mining activity at a few sites. The Khibiny Massif is one of the mining areas with the most events. Obtaining accurate automatic solutions for events from this and other mining areas will lead to a considerably lower workload for the analyst, and will consequently allow more time to be spent analyzing events of particular interest.

Method

The automatic method applied in this study consists of the following steps:

1. The IMS detects and locates a seismic event within a given distance from the target region.
2. For each phase detection by a station in the network, the estimated arrival time is refined using the method of Pisarenko et al (1987) (see Section 7.2). A standard deviation is assigned to each refined estimate.
3. For each phase detection by one of the arrays, an "optimum" frequency band for F-k analysis is extracted from a data base which we assume has been previously established and calibrated.
4. Broad-band F-k analysis is then applied to each phase. The resulting values are corrected for systematic bias and assigned a standard deviation, based upon SNR, phase type and previously observed calibration information.
5. The LocSat program (Bratt and Bache, 1988) is then applied to the revised data set, and a new event location estimate is obtained. In practice, zero depth is assumed a priori in the automatic process.

In the case study discussed in detail in this paper, we will analyze events in the Khibiny Massif recorded by IMS, for which we have independent location information. We will primarily make use of the Apatity array, using arrival times for the P and S phases and azimuths derived from the Rg phase in order to refine the location estimates as described above. In addition, we will consider possible improvement in the location accuracy when using additional available stations.

Data

The data for this study comprises 58 events at 6 mines in the Khibiny Massif. The mines are only a few kilometers apart (Mykkeltveit, 1992), and they each have a dimension ranging from a few hundred meters to about 1 km. These dimensions are small enough so that we ignore the areal extent of each mine. A list of the event parameters is given in Section 7.2.

To obtain an initial location, we have used the automatic IMS epicenter solution for each event. The automatic IMS solution relative to the "true" epicenter for each of the events is displayed graphically in Fig. 7.3.2. Although many of the events are very accurately located (to within a few km), there is a fair amount of scatter in the location estimates. The median "error" is 10.6 km. In a few cases, the location is wrong by several tens of km; this is due to occasional erroneous phase identification by the automatic process.

The Apatity array has been described by Mykkeltveit et al (1992), and initial data analysis results have been presented by Ringdal and Fyen (1992). The latter paper discusses in particular the high stability of azimuth estimates using the Rg phase for shallow events at local distances.

In Section 7.2, some examples of Apatity array recordings of events in the Khibiny Massif are shown. The filtered recordings (0.8-2.0 Hz) are dominated by the Rg phase. In contrast, the P and S phases are far more high-frequent, as is to be expected at such close distances. Because of the low frequency of the Rg phase, this phase has a high coherency across the array and thus provides more stable slowness estimates than are obtained from the other phases.

For the present study, we have used Apatity array recordings for all 58 events. For all but six events, high-frequency three-component data from the array site have been available. Furthermore, all events have associated 3-component broadband recordings from the station installed in the town of Apatity, 15 km from the array site. ARCESS array data have been available for all but one of the events.

Results

In the following, we present results from analyzing the 58 events in the data base under various scenarios. Each scenario assumes that we have an operational situation in which a certain amount of calibration information has been assembled.

a) Use of Apatity array only; P and S arrival times, Rg azimuth, no calibration.

In this scenario, we assume no prior knowledge except for the "optimum" frequency bands for timing and azimuth estimation. The travel-time tables are those that the IMS uses for Fennoscandia in general, with no regional corrections.

The results are displayed in Figs. 7.3.3. We note that there is a small systematic bias, as there seems to be a trend of events being located to the north and east of the sites. This indicates that some improvement could be obtained by introducing a regional velocity model for the Khibiny area, together with regional azimuthal corrections.

Nevertheless, the scatter relative to the 6 mines in this plot (using uncalibrated Apatity array data only) is significantly reduced compared to the IMS results plotted in Fig. 7.3.2.

The improvement can be quantified by considering that the median "error" is only 3.1 km, with a worst case "error" of 6.7 km. This can be compared to the IMS results of 10.6 km and 75.3 km, respectively. Thus the reprocessing, even without regional correction, could significantly improve the precision in the epicenter solutions if incorporated in the automatic IMS processing.

b) Use of Apatity array data only, with a regional P-S travel-time bias correction and a correction for systematic Rg azimuth bias.

The resulting location plot is shown in Fig. 7.3.4. The median error is reduced to 2.1 km, and the "worst case" error is 6.1 km.

c) Use of Apatity array data plus P and S times from the 3-component station in Apatity. Regional corrections have been applied both for the array and the 3-comp. station.

The resulting location plot (Fig. 7.3.5) shows that the median error is 1.4 km, and the maximum error is 5.4 km.

d) This final scenario includes both Apatity array data, Apatity 3-comp. data and ARCESS P arrival times. Regional corrections have been applied for all the data.

The resulting location plot (Fig. 7.3.6) shows a median error of 1.6 km, and a maximum error of 7.1 km. It is interesting to note that this is not quite as good as case c). Thus, it is not necessarily an improvement to add data, even if (as in this case) the additional data are extremely accurate (error ≤ ± 0.05 seconds on P-recordings).

We should note that the travel-time corrections used in this paper are *relative* and based upon the same data set that we have evaluated. In view of the large number of events, the possible bias introduced by this procedure should be negligible. As the origin time of the Khibiny events are unknown, we have fixed the travel-time correction of P at the Apatity three-component station APZ9 to 0. The P phase at APZ0 has travelled a shorter distance and spent less time in the earth than the other phases used in the event locations. Thus, the influence of an erroneous travel-time model is likely to be the least for this phase.

Travel-time corrections:

P	APZ9	0 s (fixed)
P	APA0	-0.10 s
Pn	ARCESS	-0.31 s
S	APZ9	0.22 s
S	APA0	0.09 s

Conclusions

In this study we have conducted extensive off-line analysis of 58 mining explosions in the Khibiny Massif recorded at the Apatity array. Independent locations of these explosions are provided by seismologists from the Kola Science Centre. Most of these events show clear P, S and Rg phases at the nearby Apatity array located 30-50 km away from the mining areas and the events have also been detected by the ARCESS array. By using the onset-time estimator of Pisarenko et al (1987) and comparing to the best manual pick, we have found that P-onsets can be automatically estimated with an accuracy of better than 0.1 seconds, and S-onsets with an accuracy better than 0.5 seconds. In addition, the azimuth estimates from F-k analysis of the P and Rg phases show to be accurate well within ± 5 degrees after removing the biases. The key to achieving stable azimuth estimates is to process the data in a fixed frequency band, using a fixed time window positioning, as demonstrated by Kværna and Ringdal (1986) for Blåsjø recordings at NORESS.

Our observations suggest that based on data from the Apatity array alone, we are able to locate these events (assuming 0 depth) with a median error of about 3 km relative to the true location. Even better accuracy can be achieved using calibration information, i.e., correcting the azimuth and arrival time observations for systematic bias. The excellent precision of the automatic phase onsets and azimuth estimates also indicate that the need for subsequent manual analysis of these events may be eliminated.

After we have established the tuned processing parameters for events in this region, a natural next step will be to automatically activate such intelligent post-processing every time the IMS locates an event in the Khibiny region. Extensions of the method to other mining areas will also be considered.

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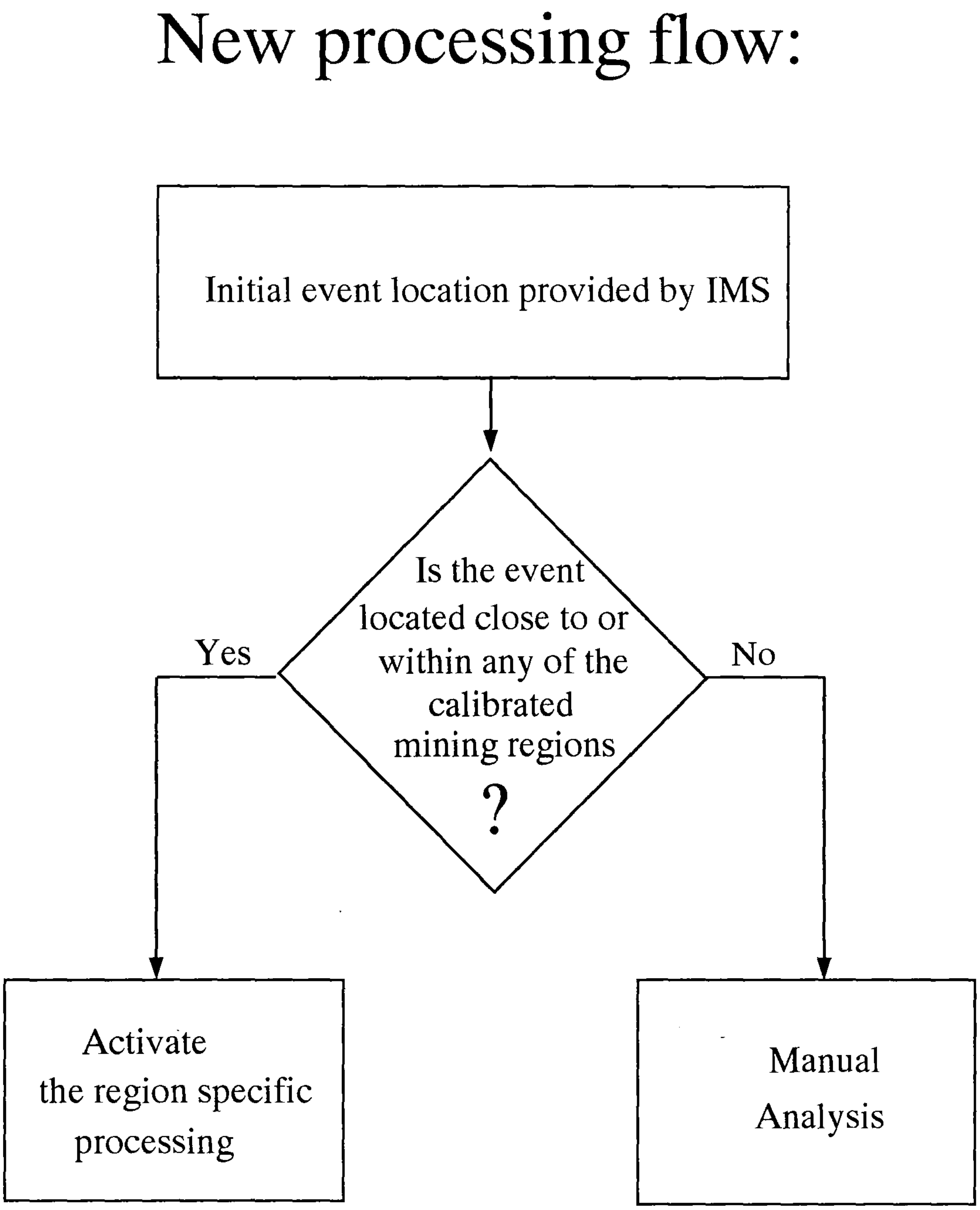

Fig. 7.3.1. Schematic view of the principle behind intelligent post-processing of seismic events.

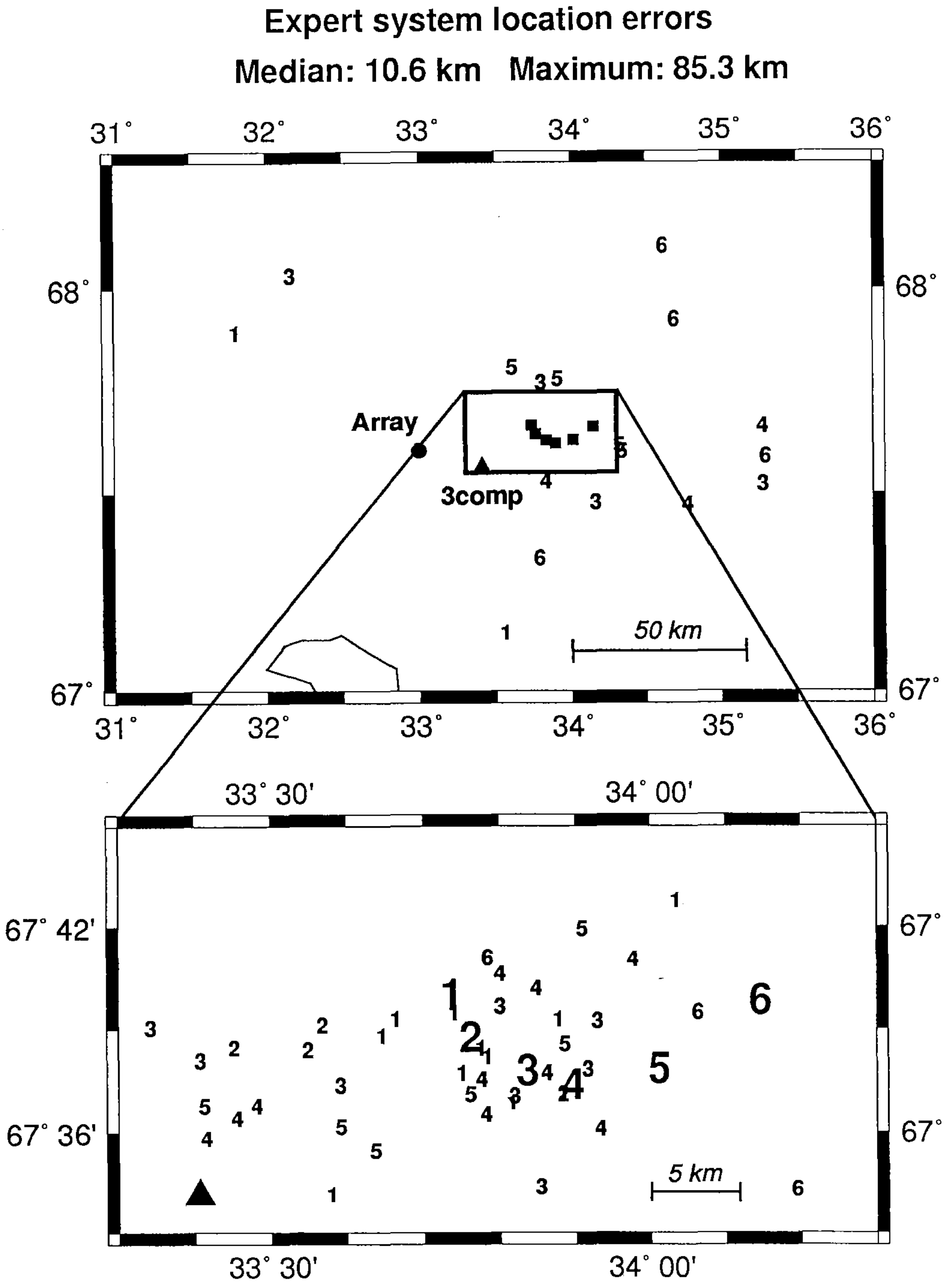

Fig. 7.3.2. Location of the six mining sites in the Khibiny Massif (large numbers 1-6) and the locations of the 58 reference events (small numbers 1-6) as given by the automatic IMS processing. In the **upper part**, a large reference area is shown, with the mines plotted as filled squares. The **lower part** shows a detailed picture for the area near the mines. The small number (1-6) associated with each event represents the mine in which the event actually occurred. The Apatity array is shown as a filled circle and the three-comp. station in the town of Apatity is shown as a filled triangle.

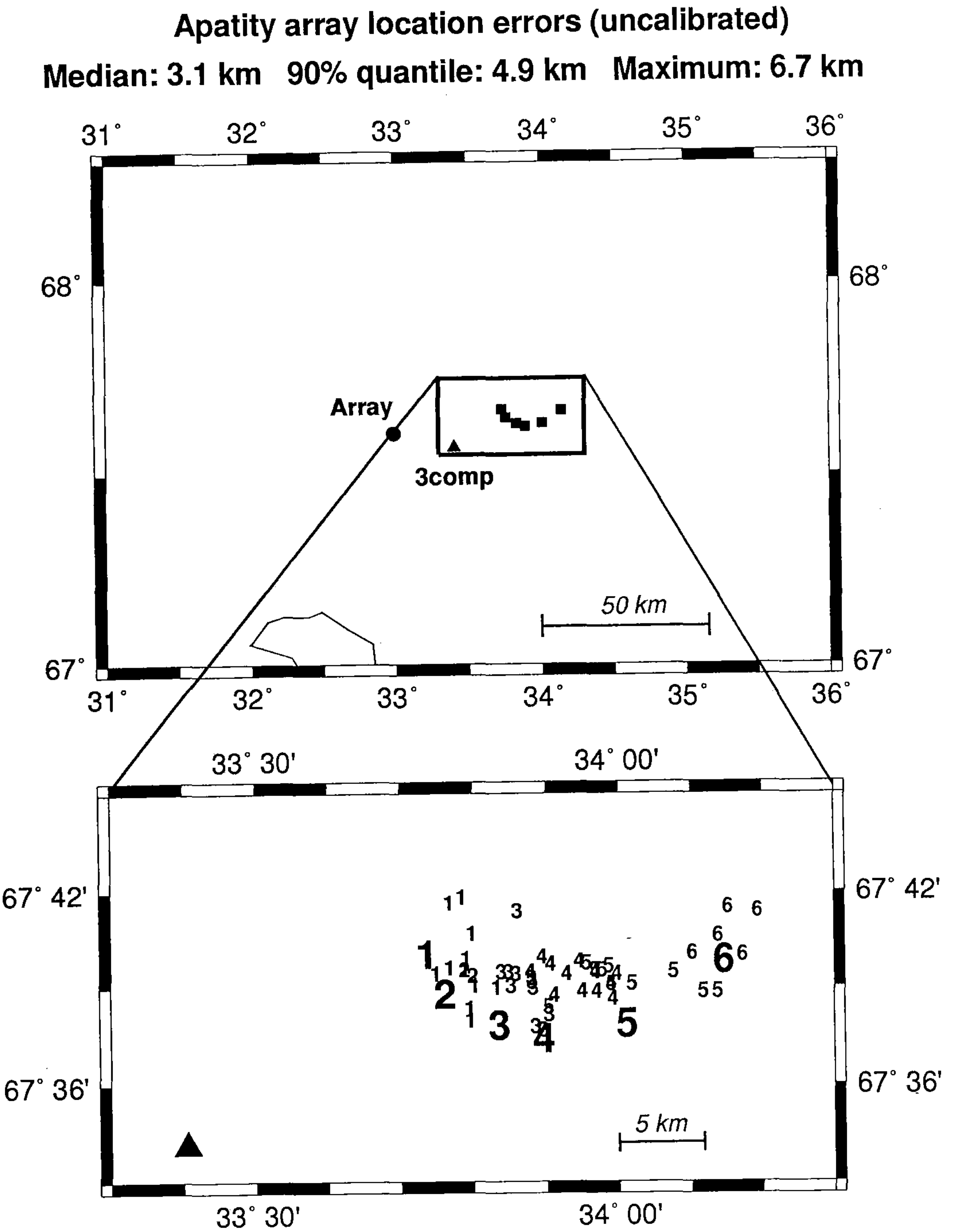

Fig. 7.3.3. Same as Fig. 7.3.2, but the event locations (small numbers) have now been taken from the post-processing results using uncalibrated Apatity array data only.

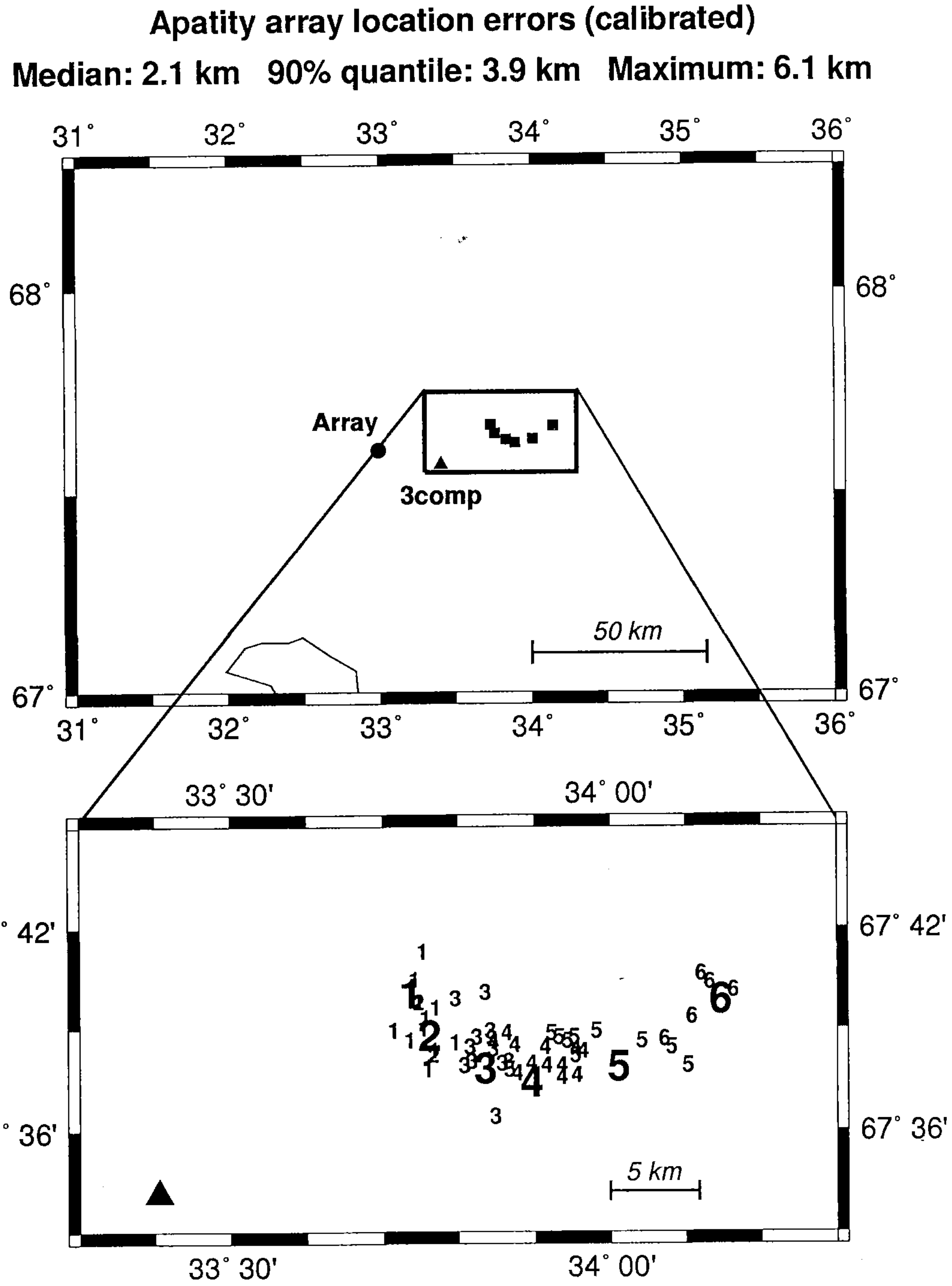

Fig. 7.3.4. Same as Fig. 7.3.2, but with the event locations resulting from post-processing of calibrated Apatity array data (see text for details).

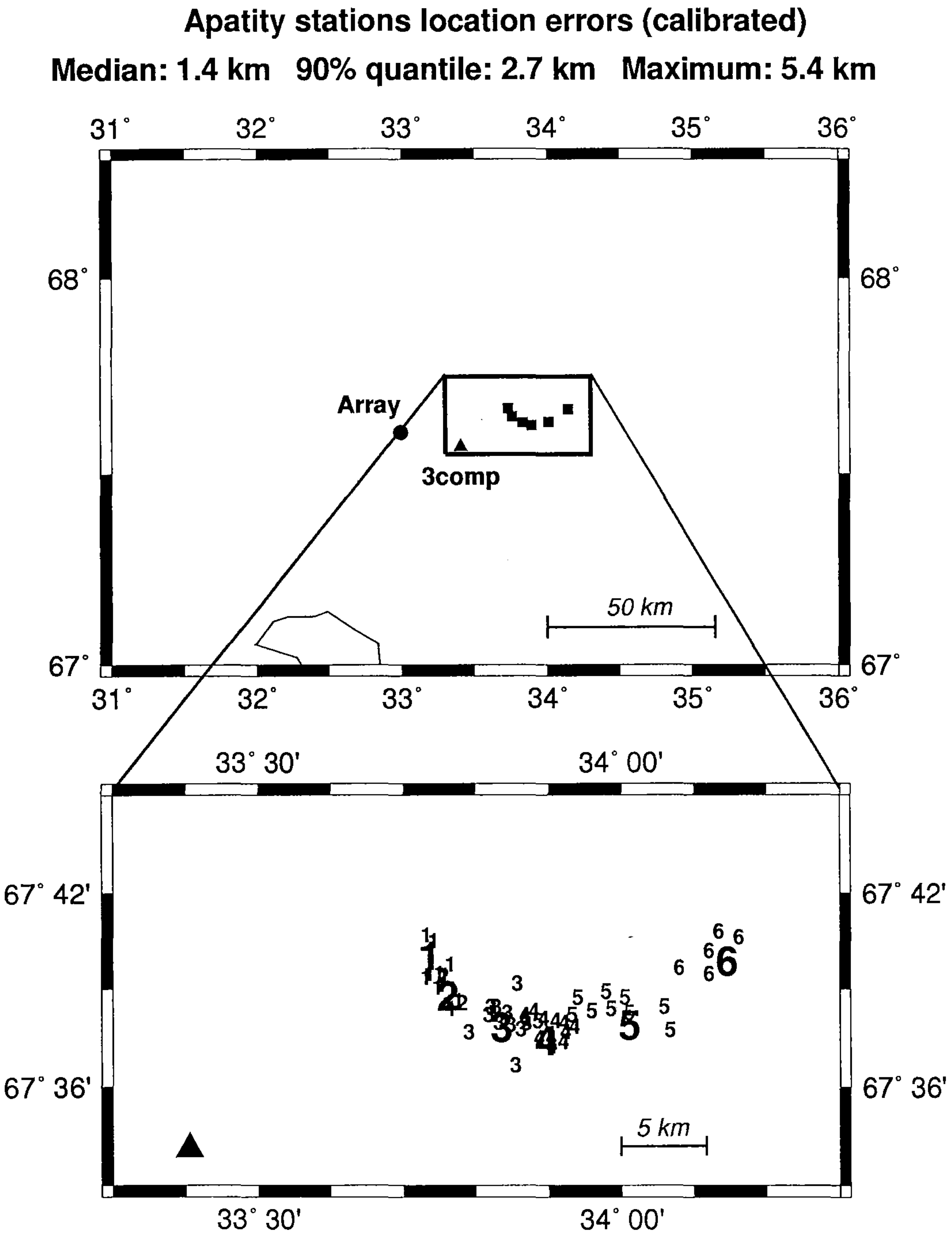

Fig. 7.3.5. Same as Fig. 7.3.2, but with the event locations resulting from combining Apatity array data and 3-comp. data (both calibrated) in the post-processing.

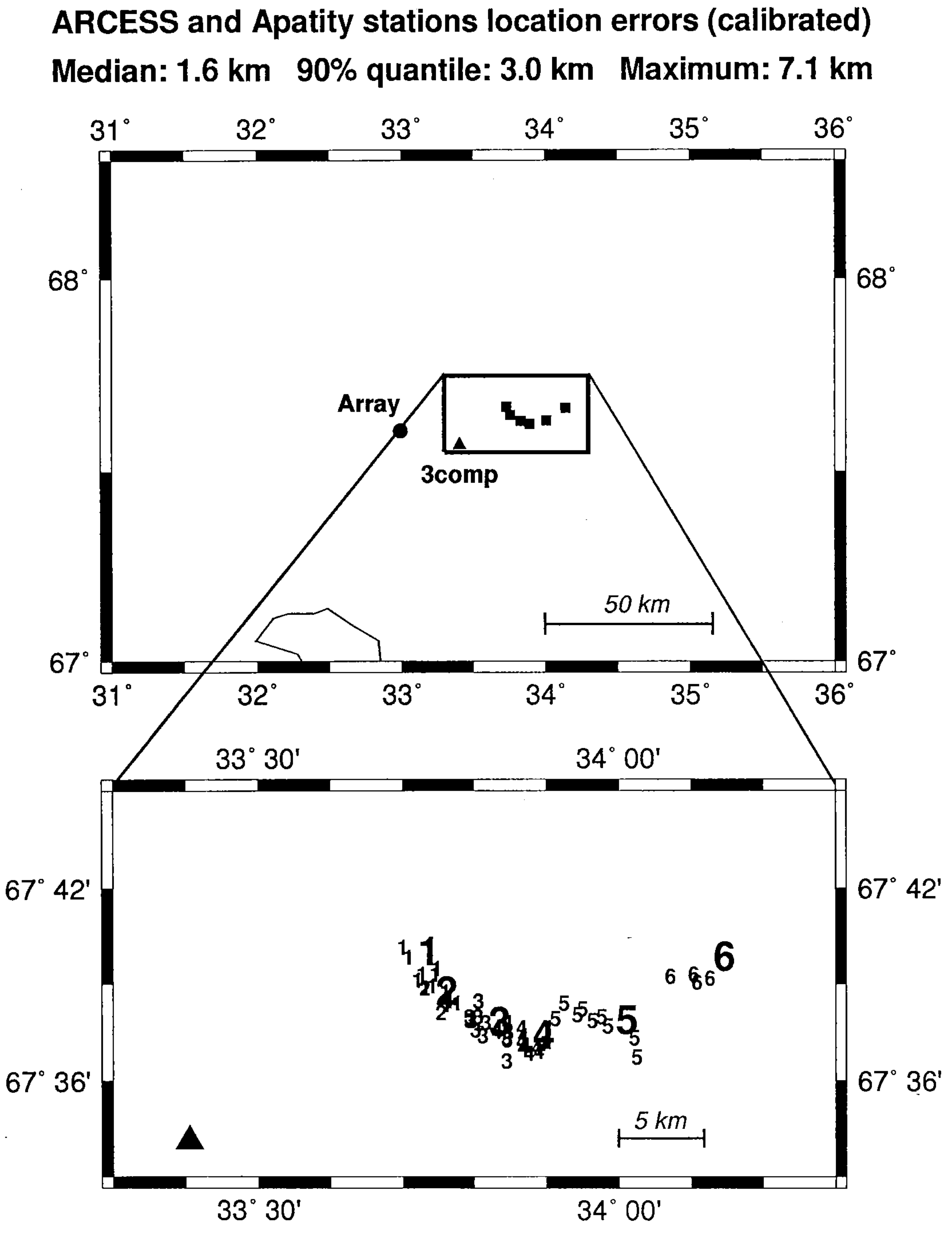

Fig. 7.3.6. Same as Fig. 7.3.2, but with the event locations resulting from combining Apatity array, Apatity 3-comp. and ARCESS array data (all calibrated) in the post-processing.