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Epicentre accuracy based on seismic network criteria

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SUMMARY

We establish reliable and conservative estimates for epicentre location accuracy using data that are readily available in published seismic bulletins. A large variety of seismic studies rely on catalogues of event locations, making proper assessment of location uncertainty critical. Event location and uncertainty parameters in most global, regional and national earthquake catalogues are obtained from traditional linearized inversion methods using a 1-D Earth model to predict traveltimes. Reported catalogue uncertainties are based on the assumption that error processes are Gaussian, zero mean and uncorrelated. Unfortunately, these assumptions are commonly violated, leading to the underestimation of true location uncertainty, especially at high confidence levels. We find that catalogue location accuracy is most reliably estimated by station geometry. We make use of two explosions with exactly known epicentres to develop local network location (0°–2.5°) accuracy criteria. Using Monte Carlo simulations of network geometry, we find that local network locations are accurate to within 5 km with a 95 per cent confidence level when the network meets the following criteria: (1) there are 10 or more stations, all within 250 km, (2) an azimuthal gap of less than 110°, (3) a secondary azimuthal gap of less than 160° and (4) at least one station within 30 km. To derive location accuracy criteria for near-regional (2.5°–10°), regional (2.5°–20°) and teleseismic (28°–91°) networks, we use a large data set of exceptionally well-located earthquakes and nuclear explosions. Beyond local distances, we find that the secondary azimuthal gap is sufficient to constrain epicentre accuracy, and location error increases when the secondary azimuthal gap exceeds 120°. When station coverage meets the criterion of a secondary azimuth gap of less than 120°, near-regional networks provide 20 km accuracy at the 90 per cent confidence level, while regional and teleseismic networks provide 25 km accuracy at the 90 per cent confidence level.

Key words: epicentre accuracy, seismic calibration.

1 INTRODUCTION

Currently almost all published earthquake catalogues have applied traditional, iterative linearized inversion schemes and 1-D Earth models to obtain event location and uncertainty parameters. Although there is a considerable effort to develop non-linear inversion schemes to estimate event locations and the corresponding uncertainties (Sambridge & Kennett 2001; Rodi *et al.* 2002), as well as efforts to apply 3-D Earth models for traveltime predictions (Antolik *et al.* 2001; McLaughlin *et al.* 2002a; Ritzwoller *et al.* 2003), these methods and Earth models have yet to find their way into routine production of earthquake catalogues. Furthermore, the goal of most catalogue producers is to achieve completeness to the lowest possible magnitude, which is at odds with the goal of maintaining uniformly accurate locations. As a result catalogues are ‘contaminated’ with poor quality locations.

Analysis of seismic location accuracy is traditionally based on calculations of formal uncertainty. Most location algorithms rely on one of two methods to determine uncertainty. The first is based on the F-statistic, where the *a posteriori* residual distribution is mapped to a location confidence ellipsoid (Flinn 1965). The second is based on the chi-square statistic, where *a priori* uncertainty for phase picking and traveltime prediction are mapped through the location algorithm to produce a coverage ellipsoid (Evernden 1969). Proper application of either technique requires compliance with basic statistical assumptions: Gaussian, zero mean, uncorrelated error processes. A number of studies suggest that these assumptions are violated in most seismic locations. Picking error tends to have ‘heavy’ tails (Buland 1986) and may be multimodal. The mean of the traveltime prediction errors is typically not zero and traveltime prediction errors are typically correlated for similar ray paths (e.g. Myers & Schultz 2000a).

Violation of statistical assumptions results in the underestimation of the true uncertainty in formal calculations (Myers & Schultz 2000a). Perhaps the most critical and commonly violated assumption is that traveltime prediction errors are unbiased. The use of a 1-D model to predict traveltimes in the 3-D Earth results in traveltime bias along specific paths. A classic example of traveltime prediction bias resulting from unmodelled 3-D Earth structure is the Long Shot nuclear explosion (Herrin & Taggart 1968). In this case, travel paths to many stations sample subducted oceanic lithosphere with high seismic velocity, causing arrival-time predictions for these paths to be systematically late. Using large numbers of arrivals (the prediction errors of which are assumed to be uncorrelated) in the location results in a small formal error ellipse (139 km^2). However, the actual location error is 26 km, well outside of the confidence ellipse. A well-known example of local network location bias occurs on the San Andreas fault, where seismic velocities are faster on one side of the fault than the other. Dewey & Kork (2000) showed that the location bias is as high as 5 km for events that are well recorded on a local network in Central California.

Seismic catalogues are used in a wide variety of studies ranging from seismic hazard assessment to the development of Earth models. For example, it was recognized early on that accurately located events are needed to develop and test improved traveltime tables and earth models. Herrin (1968) used arrival times from nuclear explosions with precisely known hypocentres and origin times to construct traveltime tables, bypassing the issue of location uncertainty for earthquakes. However, spatial sampling is limited when only explosions are used to construct global models, so Kennett & Engdahl (1991) augmented explosions with what they considered to be well-located earthquakes. Although the goal of using well-located events was to obtain a location accuracy of 5 km, this level of accuracy was only a best guess.

It is clear that formal uncertainties reported in earthquake catalogues cannot be taken at face value. On the other hand, it is impractical for researchers to relocate every event in a catalogue if they wish to control location accuracy. We believe that a reasonable compromise is to develop methods for reliably gleaning location accuracy from catalogues by assessing network coverage on an event-by-event basis.

1.1 Review of location accuracy assessment

Interest in earthquake location accuracy has a long history, but in recent years, research on improved location accuracy has been driven by efforts to effectively monitor the Comprehensive Nuclear Test Ban Treaty. Much of the recent work is not published in the open literature. Here we review recent published and unpublished efforts that have contributed to the methods and findings presented below.

Kennett & Engdahl (1991) assessed global location accuracy for a data set of 104 events (21 nuclear explosions and 83 well-located earthquakes) in the course of developing the IASP91 velocity model and found an average epicentral location error (using IASP91) of 14 km.

Sweeney (1996) investigated the feasibility of selecting 'reference events' (events where the hypocentres can be considered known to high accuracy, typically, less than 5 km) from global bulletins, such as those of the International Seismological Centre (ISC) and National Earthquake Information Centre (NEIC), that contain predominantly teleseismic arrival time data. He suggested that locations from these catalogues have an accuracy of 10–15 km when the azimuthal gap—the largest open azimuth between recording stations—is less than 200° and at least 50 phases are used. Sweeney (1998) revisited these selection criteria and found 15 km (or better) epicentre accuracy for teleseismic networks with an azimuthal gap of less than 90° and with at least 50 defining phases.

Engdahl *et al.* (1998, hereafter EHB) produced a 'groomed' ISC catalogue by using a modern Earth model (ak135), later phase (including depth phases) arrival times, and station-specific traveltime corrections. They assessed the location accuracy of their procedures by relocating a data set of 1166 nuclear explosions plus the 83 earthquakes used as test events by Kennett & Engdahl (1991) and estimated an average mislocation vector of 9.4 ± 5.7 km. All of the test events had an azimuthal gap of less than 180°.

Myers & Schultz (2000b) re-examined the EHB data set (ignoring subduction zone events) and reached a similar conclusion, estimating 15 km (or better) epicentre accuracy at the 95 per cent confidence level for events with an azimuthal gap of less than 90°. These criteria were used by several studies (Myers & Schultz 2000a; Steck *et al.* 2001) for selecting 'calibration' events to develop and validate empirical source-specific station correction (SSSC) surfaces to attempt to account for lateral heterogeneity in regional seismic monitoring efforts.

Bondár *et al.* (2001) introduced the nomenclature of 'ground truth' categories (GTX, where 'X' designates epicentre location accuracy in kilometres (the true epicentre lies within 'X' km of the estimated epicentre) to describe the location accuracy of events in the Ground Truth data set assembled at the Centre for Monitoring Research (CMR). Events satisfying Sweeney's (1998) criteria were accepted as GT25, while for GT10 at least five stations, all within 2° distance, and with an azimuthal gap of less than 180° for stations within 5° distance, were required, basically prescribing a local network solution.

For local and regional earthquakes, Dewey *et al.* (1999) established 'stringent' and 'relaxed' criteria to select events with 10 km accuracy using the NEIC bulletin. Their stringent selection criteria require that events are greater then $mb = 3.5$ and located with (1) at least 10 stations, all within 250 km from the epicentre, (2) at least one station within 30 km and (3) an azimuthal gap of less than 90°. Their relaxed criteria require a maximum 180° azimuthal gap, at least five stations, all within 250 km, and at least one station within 30 km. They validated the selection criteria by locating the events with random sparse subsets of stations and compared the locations to those obtained by using all stations. Events meeting either criterion are considered to be only 'candidates' for GT10 status. To be accepted as GT10, the regional network solution must agree (to within 5 km) with a local network solution that uses a local velocity model, and the semi-major axis of the 90 per cent confidence ellipse must be less than 5 km. Dewey & Kork (2000) pointed out that some of the events selected by the stringent criteria may be accepted as GT5 if the local network location of the event is within 2.5 km of the regional network location and the semi-major axis of the 90 per cent confidence ellipse is less than 2.5 km, and the event is not in a source region with known high bias. These are exceptionally strict requirements that are intended to have a confidence level approaching 100 per cent.

McLaughlin *et al.* (2002b) adopted Dewey *et al.*'s (1999) stringent criteria in a somewhat relaxed form to select GT5 events. The selection criteria for candidate GT5 events required that shallow-focus events are located with at least 10 stations, all within 250 km from the epicentre, with an azimuthal gap of less than 120°, and at least one station within 30 km. However, Myers & Shultz (2001) had already pointed out that these criteria are not stringent enough. Using the Dead Sea calibration explosion, they selected random subsets of stations that satisfy these criteria and relocated the event. The comparison with the GT0 location of the explosion demonstrated that location accuracy is 12 km at the 95 per cent confidence level and mislocation can be as high as 20 km. In Section 3.2, we revisit these criteria.

While these studies reveal some broad principles regarding the factors that seem to be most important in reliably estimating location accuracy for earthquake catalogues, there are considerable discrepancies between the results of different studies. It has not been possible to extract from them a generally applicable set of criteria that can be applied at all distance ranges. In some cases, this is because the study was of limited scope; in others, because the accuracy of the test data set was inadequately controlled. Obviously, some of the variance has its origin in the different conceptions of what level of uncertainty is 'good enough'. We seek to improve matters in this study by applying a consistent style of analysis to a large data set of epicentres with exceptionally well-known source parameters. We derive criteria for estimating location accuracy of epicentres—for earthquakes and nuclear explosions—determined with local, regional, and teleseismic networks.

2 DATA SETS

We assembled a data set of globally distributed seismic events that were well recorded at regional and teleseismic distances and where the absolute locations and origin times are known to higher accuracy than is typical of even the best global earthquake catalogue (Fig. 1). There are currently 1905 events in the data set, including 1234 explosions, most with source locations known to 2 km or better, and 671 earthquakes where the locations are believed to be accurate to at least 5 km. For this reason we refer to this data set in the rest of this paper as the GT5 data set. This is easily the largest and best-controlled set of 'test events' to be used in a general analysis of earthquake location accuracy. It is used in this study to establish generally applicable criteria for estimating location accuracy of standard catalogue epicentres over regional and teleseismic distance ranges.

2.1 Fiducial explosions

The highest quality reference events are those for which man has controlled the source process and can therefore determine the location and origin time to near perfect accuracy for seismic purposes. To test local networks, where location accuracies of 5–10 km are the goal, this type of highly accurate test event is needed.

In 1999 November three calibration explosions were detonated in the Dead Sea (Gitterman & Shapira 2001). The yields for these explosions were 0.5, 2 and 5 tonnes of TNT. The smallest explosion was recorded only at the closest stations, but the two larger events were recorded at stations in Israel, Jordan, Lebanon and Syria, to distances of 250 km. The combined local network provides excellent network coverage with considerable azimuthal redundancy. Records of the 5 ton explosion are highest in quality and are therefore used in this study. *P*-wave picks were provided through the Eastern Mediterranean Seismological Centre and directly from the Geophysical Institute of Israel. *S*-wave arrivals are not evident in the records for these underwater explosions.

On 1992 November 2 an ammunition storage site in the Swiss Alps exploded. The accident killed six people and blasted off approximately 1×10^6 m^3 of rock (Kradolfer 1997 Pers. comm.). The nominal yield for the explosion is 0.83 kilotons of TNT. While the epicentre and depth are tightly constrained, the exact time of the explosion is not known and the best estimate of origin time is from the 'fixed location' using the stations of the Swiss Seismological Service. For our purposes, the small uncertainty in origin time does not disqualify the event from fiducial status. Fig. 2 shows the local station distribution for the Dead Sea explosion (Fig. 2a) and the Swiss explosion (Fig. 2b).

To our knowledge, these are the only GT0 events with the requisite station coverage at local distances to carry out a Monte Carlo location simulation. Both explosions lie in rather complex regions where strong heterogeneity in crustal structure can be expected. Because of the complex geology, the analysis of these events should provide conservative estimates of location accuracy, as simpler geological settings are likely to yield more accurate locations.

The major nuclear test sites contribute a large number of seismic sources where the locations and origin times are often known with sufficient accuracy to be considered fiducial. These data are obtained from the CMR Ground Truth and Explosion data sets (Bondár *et al.* 2001; Yang *et al.* 2003). There are currently 1234 explosions in the data set, most with source locations known to 2 km or better. For each event, the associated phase arrival times (mostly at regional and teleseismic distances) are primarily taken from the ISC catalogue.

2.2 Well-located earthquakes and explosions

Because of the limited geographic distribution of nuclear explosion data, we have assembled a data set of 671 earthquakes where the source parameters (especially epicentre) are known with exceptional

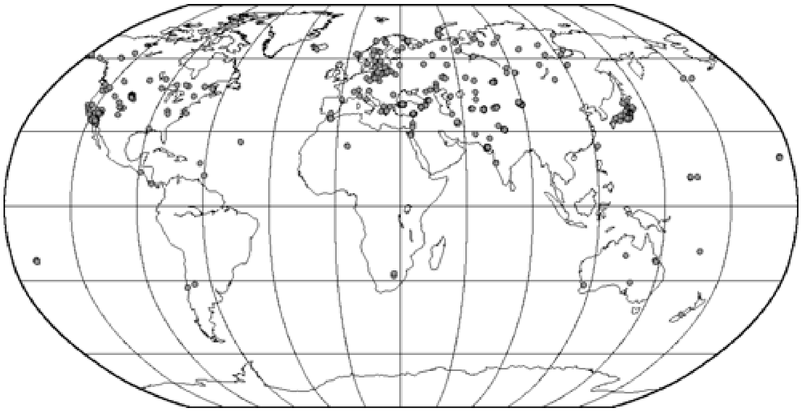

Figure 1. Locations of 1905 events in the test GT5 data set used in this study. Events are globally distributed but concentrated in the northern hemisphere, especially North America, Europe, Central Asia and Japan.

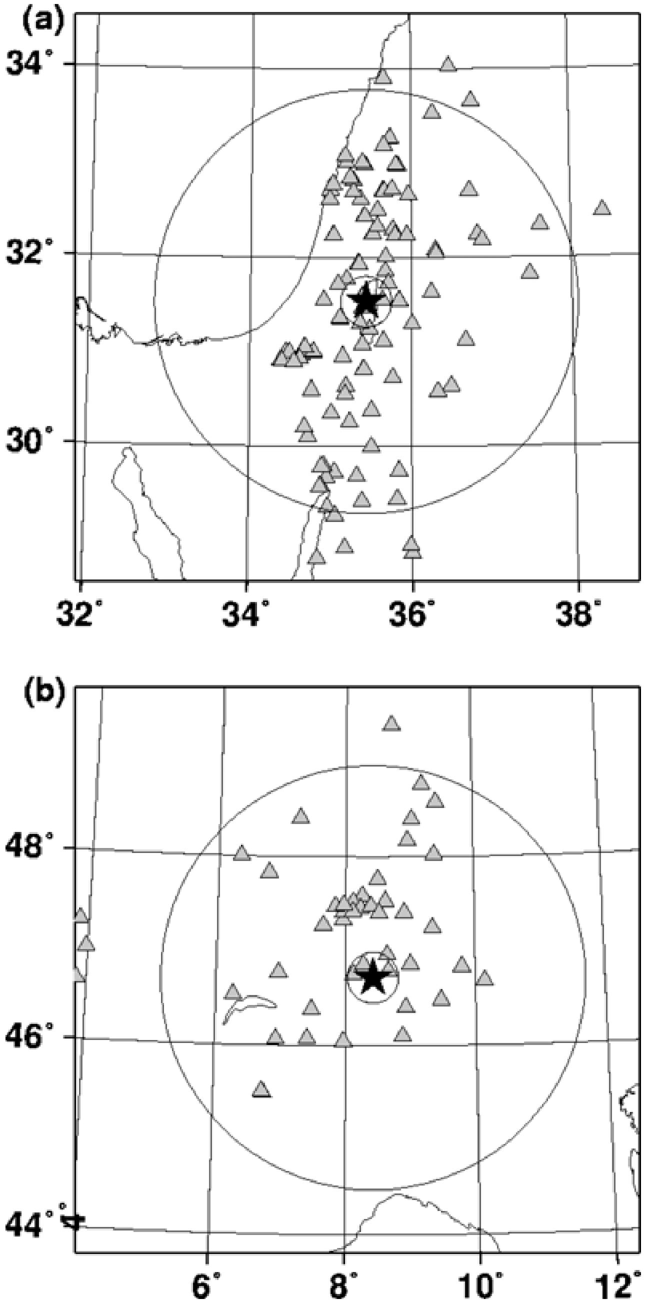

Figure 2. Local network geometry (triangles) of (a) the 1999 November 11 Dead Sea calibration explosion and (b) the 1992 November 2 ammunition storage explosion in Switzerland. The 30 and 250 km circles around the epicentres (stars) are also drawn.

accuracy. This work follows on the pioneering efforts of Kennett & Engdahl (1991). Some of the nuclear explosion data in our study belongs in the category of 'well-located' rather than 'fiducial' because the source parameters were derived from careful seismological analysis rather than provided by the original organizations that conducted the shots. Engdahl & Bergman (2001) provided a large number of the well-located earthquakes and nuclear explosions that have been carefully validated by multiple event location methods. As with the nuclear explosion data, the repository for the earthquake data is the CMR Ground Truth and Explosion data sets (Bondár *et al.* 2001; Yang *et al.* 2003). We have used only events for which the estimated epicentre accuracy is 5 km or better.

On 1998 May 28 Pakistan carried out its first underground nuclear explosion. The event was well recorded at teleseismic distances and both Albright *et al.* (1998) and Barker *et al.* (1999) determined the epicentre to be under the same mountain, using satellite imagery. Since the two epicentres are 4.5 km from each other, we consider the event to be located at GT5 accuracy. This event is of particular interest to us, because, unlike nuclear explosions at the major test sites, the arrival time data for this event has to a great extent been picked by analysts lacking detailed *a priori* knowledge of the location of the test. The significance of this fact is discussed further below.

Clustered events in the GT5 data set have been validated by the hypocentroidal decomposition (HDC) method (Jordan & Sverdrup 1981) for multiple event relocation. We seek situations where a number of moderate-size explosions or earthquakes are clustered (within approximately 50–100 km of each other), where the cluster includes one or more of the fiducial explosions, or, in the case of earthquakes, one or more events that have been very well located by a local network. We refer to these as 'reference events'. The events in the cluster may be widely distributed in time. We validate the locations by requiring that the relative location patterns of reference events are consistent with the pattern of the corresponding cluster vectors from the HDC analysis. Discrepancies may be resolved by determining that the cluster vector is biased for some reason, or by rejecting a candidate reference event. For this reason, most of the clusters contributing to the data set for this study are calibrated by several reference events. Absolute locations of clustered events are tied to those of the reference events by HDC analysis, and those with sufficiently small confidence ellipses are added to the GT5 data set.

3 DISTANCE-BASED NETWORK CATEGORIES

For this study, a modified version of the algorithm developed by Engdahl *et al.* (1998) was used to perform the relocation of all events in the GT5 data set. This is a single-event location procedure that uses the ak135 traveltime model (Kennett *et al.* 1995), and features both dynamic phase identification and weights based on the inverse of previously determined phase variances as a function of distance. Outliers are removed dynamically by truncation: 7.5 s for arrivals up to 28° surface-focus distance and 3.5 s at larger (teleseismic) distances. For these relocations, depths were fixed at the depth of the reference event, only first arriving P waves were used as defining phases, and no station-specific corrections were applied. Ellipticity and elevation corrections were, however, applied to the predicted traveltimes. Convergence (i.e. changes in location and origin time of less than 0.1 km and 0.01 s, respectively) was usually achieved after several iterations regardless of the station distribution.

Fig. 3 shows the distributions of first-arriving P-wave traveltime residuals based on cluster locations in the test GT5 data set for earthquakes (left) and explosions (right) in near regional, regional and teleseismic distance ranges. The traveltime distribution patterns of earthquakes and explosions are strikingly different at near-regional and regional distances. The distributions for explosions at these distances have a sharp peak superimposed on a broader distribution that is similar to that of the earthquake population. Therefore, we treat the earthquake and explosion populations separately and rely on the earthquakes when deriving selection criteria for candidate reference events. We further discuss the discrepancy between the earthquake and explosion populations in Section 4.1.

By comparing the results of the single-event relocations described above with the known epicentres from the GT5 data set, we examine

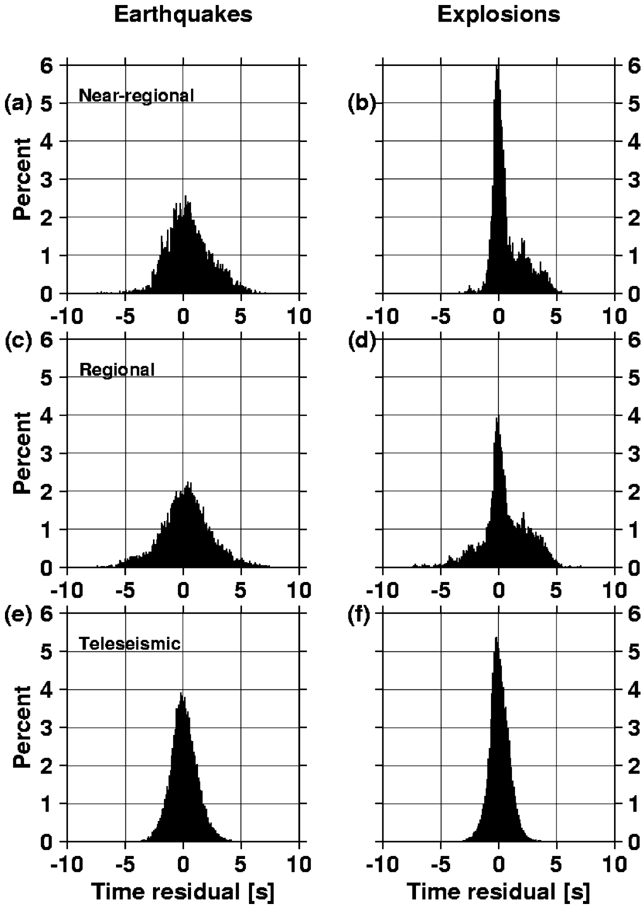

Figure 3. Traveltime residual distributions of first arriving *P*-waves from earthquake and explosion clusters in the test GT5 data set. The vertical axis indicates the percentage of the observations in a bin relative to the total number of observations. All residuals are from defining phases, with cluster origin times adjusted to fit the ak135 model. (a) Earthquakes, near-regional distance range (2.5°–10°), (b) explosions, near-regional distance range, (c) earthquakes, regional distance range (2.5°–20°), (d) explosions, regional distance range, (e) earthquakes, teleseismic distance range (28°–91°), (f) explosions, teleseismic distance range.

location accuracy for local, near-regional, regional and teleseismic networks separately. The primary utility in segregating locations by network distance is that both traveltime prediction and arrival picking statistics tend to be distinct in each distance range. We extend common definition of *local* distance (between 0° and the *Pn*/*Pg* crossover, normally approximately 2°) to include arrivals out to 2.5°. Inclusion of data at and slightly beyond the *Pn*/*Pg* crossover distance is likely to increase the location error. Our local distance criteria are, therefore, conservative estimates for local network locations.

To demonstrate the level of traveltime prediction error produced by Earth's lateral heterogeneity, source-station ray path anomalies are plotted as a function of distance for *Pn* and *P* phases (Fig. 4). Robust statistics are used to estimate these path anomalies as the median and spread (a robust analogue to the standard deviation) of repeated source-station ray paths from each cluster based on residuals of defining *P* and *Pn* phases in the GT5 data set (see Fig. 3). These path anomalies are estimated relative to the 1-D reference model ak135 and are adjusted for cluster time baseline shifts. Estimates of source-station empirical phase path anomalies (the median) are accepted with a minimum requirement of five observations and a spread of less than 1.40.

Near-regional distance is defined as 2.5°–10°. Although more conventional definitions for regional distance extend to greater distance, we find a distinct increase in *Pn* path anomalies at distances greater than 10° (Fig. 4a). Over the near-regional distance range first arriving rays travel in the crust and upper-mantle, bottoming in the lithosphere. The increase could be indicative of integration of model error over these longer paths. This jump also suggests prominent 3-D heterogeneities that cannot be accounted for by 1-D models and prompts us to treat the 2.5°–10° and the more traditional 2.5°–20° regional distance ranges separately.

We include analysis for *regional* distances between 2.5° and 20°. Between ∼13° and 20° first arrivals are interacting with upper-mantle discontinuities, producing triplications in the traveltime curve. Triplications hinder phase identification and degrade phase arrival accuracy. The result is increased traveltime prediction error for *Pn* phases (Fig. 4a) and reduced location accuracy at regional distances.

We define *teleseismic* distance as the distance range between 28° and 91°. This distance range corresponds to bottoming depths in the lower mantle (between 740 and 2740 km, the top of the D'' layer) for ak135 *P*-waves. Global networks reliably record events with magnitude 4.5 or greater at teleseismic distances. In this study we exclude *PKP* phases from locations to avoid potential errors stemming from misidentification of *PKP* branches in the distance range 125°–150°. We also exclude data in the distance range 20°–28°, which corresponds to a bottoming depth between 660 and 760 km. As noted in Kennett & Engdahl (1991) an *ad hoc* linear gradient is used to connect the empirically determined velocities above and below this depth range, resulting in traveltimes that are considered somewhat less reliable. Fig. 4(b) shows that the range of path anomalies decreases (to ±2 s) between approximately 18° and 28° and remains nearly constant and low at teleseismic distances.

3.1 GT criteria

To develop criteria for estimation of location accuracy, we rely on parameters that are routinely reported or can be easily derived from bulletin data. We have considered criteria such as the epicentral distance to the closest station (local distance), the number of stations and phases used to locate the event, the largest azimuthal gap and secondary azimuthal gap. Each criterion is considered at local, near regional, regional, and teleseismic distance ranges. We find that criteria related to geographic station coverage (azimuthal gap) are by far the most useful for estimation of location accuracy.

The largest azimuthal gap in station coverage is directly related to network geometry and provides a quantitative measure on how well an event is surrounded by stations. However, this metric is susceptible to reading errors at crucial stations, and we find that the secondary azimuthal gap is a more robust measure of network geometry and location accuracy. Secondary azimuthal gap is defined as the largest azimuthal gap filled by a single station, illustrated in Fig. 5. The secondary azimuthal gap criterion not only reduces vulnerability to picking and traveltime prediction errors at crucial stations, but it implicitly invokes constraints on both the azimuthal gap and the minimum number of stations.

We adopt the 'ground truth' GT*X* classification of Bondár *et al.* (2001) that uses the '*X*' suffix to designate location accuracy in kilometres. We modify this nomenclature to $\mathrm{GT}X_{C\,\mathrm{per\,cent}}$, where *C* per cent is the percentage confidence. For example, events that are

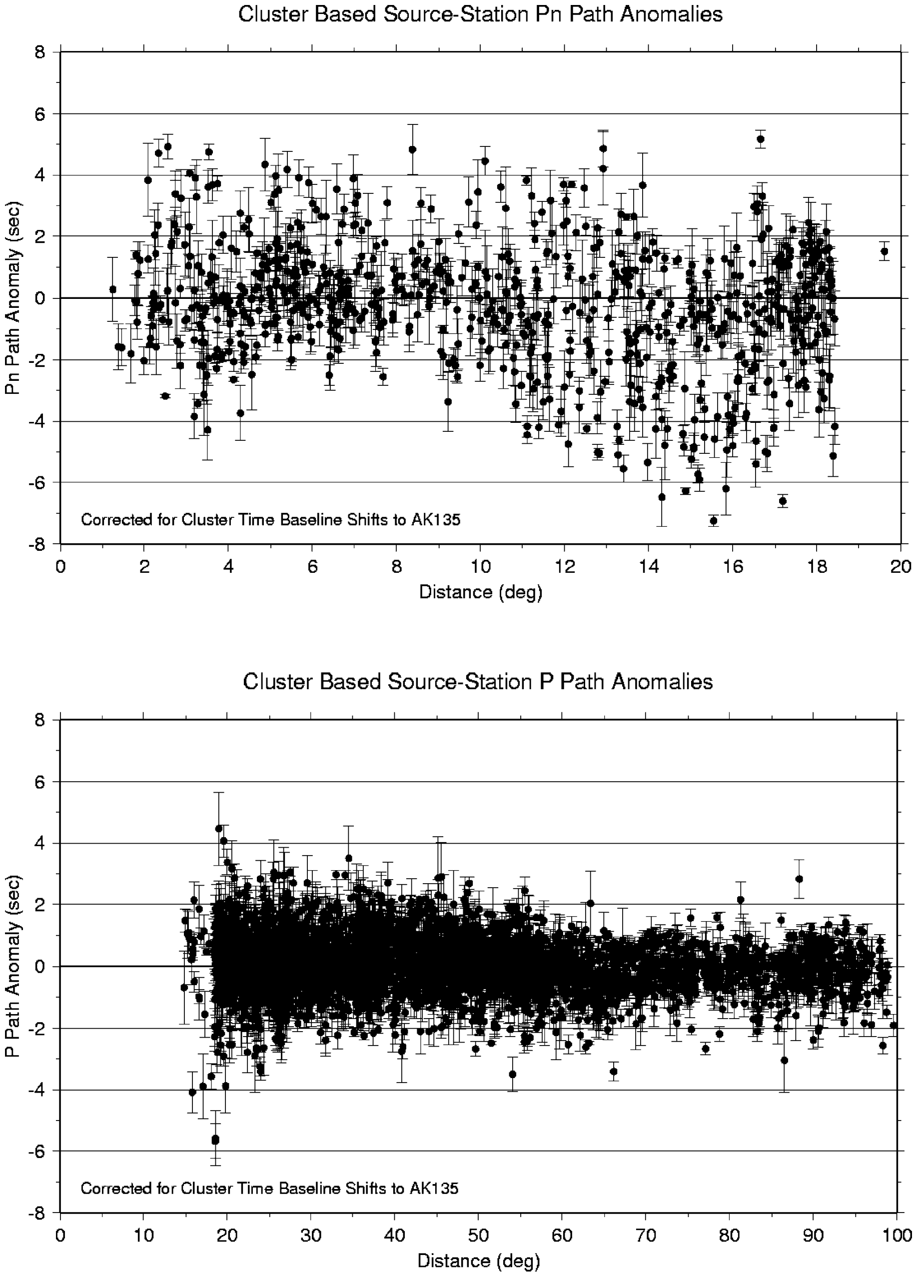

Figure 4. Empirical source-station, ray path anomalies for *Pn* (a) and for *P* (b) derived from HDC analysis of clustered events in the test GT5 data set. Repeated ray-paths provide an estimate of the median (solid dot) and spread (vertical lines) of cluster to station path anomalies. Path anomalies are corrected for cluster time baseline shifts with respect to ak135.

accurate to within 5 km at a 95 per cent confidence level are designated $\mathrm{GT5}_{95\,\mathrm{per\,cent}}$. A confidence level is more realistic than a bounding value, because we determine accuracy criteria empirically, and the possibility exists that egregious errors (clock or phase misidentification) may exist for events outside of our criteria-defining data set. For reasons discussed below, we apply accuracy criteria to epicentre parameters (latitude, longitude) only. Depth and origin time are treated separately.

3.2 Local network location accuracy criteria

The most accurate epicentres can be obtained for events inside dense, local networks. We use the 1999 November 11 Dead Sea and 1992 November 2 Swiss munitions explosions to develop and test location accuracy for local networks. We relocated each event many times with 10 randomly selected stations within 250 km of the epicentre. The choice of 10 stations is somewhat arbitrary, but typical of dense local networks. Networks with fewer stations often cannot satisfy constraints on azimuthal gap for GT5 levels of accuracy. Requiring many more than 10 stations would eliminate too many networks from consideration. 10 000 realizations were generated for each event, and the azimuthal gap, secondary azimuthal gap and number of stations within 30 km from the epicentre were measured for each Monte Carlo realization.

Fig. 6 shows the 2-D histograms of mislocation versus azimuthal gap (Fig. 6a) and secondary azimuthal gap (Fig. 6b). It is clear that it is not possible to define constraints on the network geometry

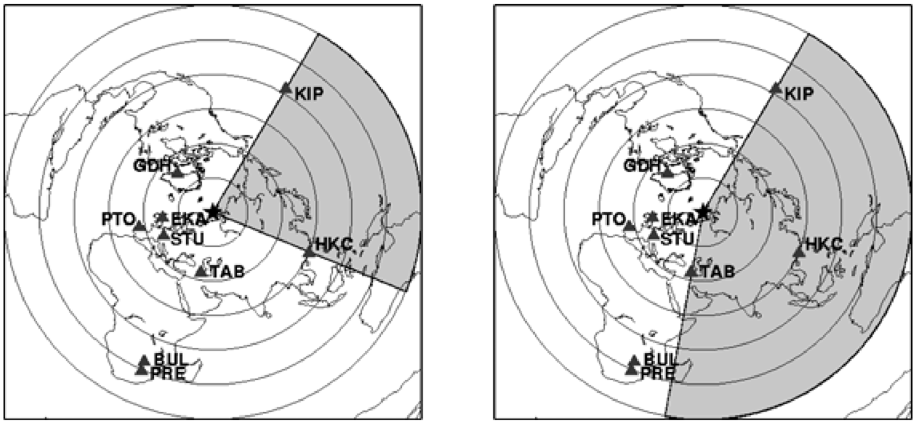

Figure 5. Illustration of primary and secondary azimuthal gaps. The recording stations (triangles) are plotted for the 1975 August 23 underground nuclear explosion (star) in Novaya Zemlya. The shaded areas show the azimuthal gap (left) and the secondary azimuthal gap (right). Although the 82° azimuthal gap indicates a quite decent coverage, any reading error at HKC that provides the 160° secondary azimuthal gap may bias the location.

that would select all events located with 5 km accuracy or better and reject those with mislocation greater than 5 km. Therefore, we specify the confidence level with which candidate GT5 events are selected. Based on the Monte Carlo simulation, we find that crustal events are located with 5 km accuracy or better at the 95 per cent confidence level if they are located:

1. with at least 10 stations, all within 250 km;
2. with an azimuthal gap of less than 110°;
3. a secondary azimuthal gap of less than 160°;
4. at least one station within 30 km from the epicentre.

The latter constraint gives some confidence in depth for crustal events. Fig. 7 shows the cumulative histogram of mislocations for all realizations (dotted line) and for those 10 station subnetworks that meet the above constraints on network geometry (solid line). The median (50th percentile) mislocation is approximately 3 km for all realizations and is approximately 2.5 km for the networks geometries satisfying our GT5 selection criteria. However, at the 95 per cent percentile the two curves diverge, indicating that 95 per cent of the events identified by the GT5 selection criteria are located with better than 5 km accuracy, while the remaining 5 per cent of events are not worse than GT10. The mislocation at the 95 per cent percentile degrades to 10 km when considering all realizations. Fig. 8 shows the distributions of the realizations satisfying the GT5$_{95\ \mathrm{per\ cent}}$ criteria (filled histograms) as a function of mislocation, depth and origin time difference relative to the true hypocentre. The GT5$_{95\ \mathrm{per\ cent}}$ selection criteria effectively cut-off the long tails of the distributions obtained from all realizations (hollow histograms), suggesting that the location accuracy criteria reduce sensitivity to outlier data. The constraints on network geometry together with the requirement of having at least one station within 30 km of the event to ensure it is at a crustal depth also helps to eliminate the bimodal distributions of depth and origin time.

3.3 Regional network location accuracy criteria

To derive location accuracy criteria for regional networks we relocate the GT5 data set using the modified EHB procedures, described in Section 1.1. As discussed above, we examine near-regional (2.5°–10°) and regional (2.5°–20°) networks separately. Fig. 9 shows the median mislocation of all test events as a function of secondary azimuth gap for near-regional and regional distances. For both distance ranges, location accuracy degrades when secondary azimuthal gap exceeds 120°. We note that near-regional networks consistently outperform networks spanning the whole regional distance range. The figure illustrates the case where more is less: adding stations from far-regional distances may result in less accurate locations.

For events with secondary azimuthal gap of less than 120° we estimate the location accuracy level from the cumulative distribution of mislocations for near-regional and regional networks (Fig. 10). In both cases, the curves for earthquakes and explosions at known test sites are clearly separated above the 40th percentile, indicating that explosions are better located as network coverage deteriorates. We conclude that the single constraint—secondary azimuthal gap of less than 120°—selects earthquakes at GT20$_{90\ \mathrm{per\ cent}}$ and explosions at known test sites at GT15$_{95\ \mathrm{per\ cent}}$ levels of accuracy when located with stations between 2.5° and 10° (near-regional distance range). For regional networks the same constraint yields GT25$_{90\ \mathrm{per\ cent}}$ for earthquakes, while the accuracy of the locations of nuclear explosions remains GT15$_{90\ \mathrm{per\ cent}}$.

3.4 Teleseismic network location accuracy criteria

For teleseismic networks we follow the same approach as for the regional case, i.e. we relocate the GT5 data set using only stations in the 28°–91° distance range. Fig. 11(a) shows the median mislocation versus secondary azimuthal gap for distances for the teleseismic distance range. As with the near-regional and regional cases, we see an increase in mislocation error at a secondary azimuthal gap of 120°. Fig. 11(b) shows the corresponding cumulative distribution of mislocations for events with secondary azimuthal gap of less than 120°. The separation of curves for earthquakes and explosions at known test sites are even further separated than in the case of near-regional and regional networks, indicating dramatically better location accuracy for nuclear tests than for earthquakes. We find that the criterion—secondary azimuthal gap of less than 120°—selects earthquakes at GT25$_{90\ \mathrm{per\ cent}}$ and explosions at known test sites at GT15$_{95\ \mathrm{per\ cent}}$.

We further validate the teleseismic criterion by performing a Monte Carlo simulation using the 1998 May 28 underground nuclear explosion in Pakistan. We believe that this explosion is a better test of location uncertainty than explosions at established test sites, where prior information concerning event location may bias analyst phase picking procedures. Furthermore, the unusual complexity

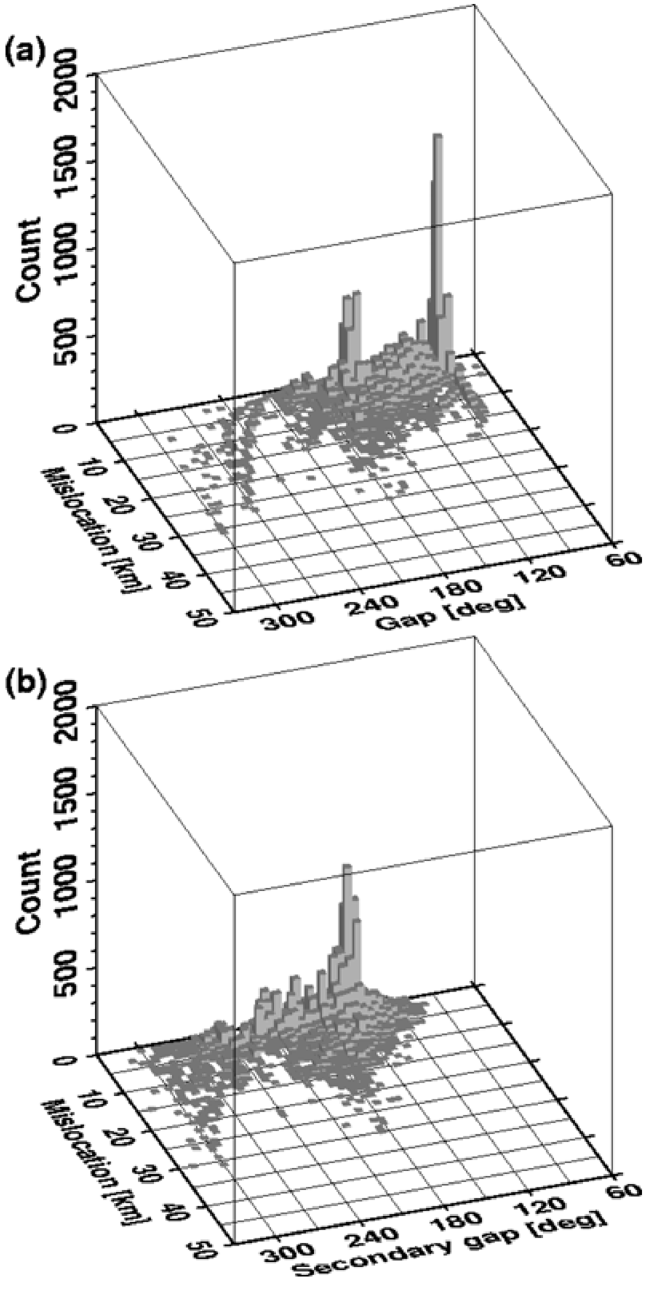

Figure 6. Histograms of mislocation versus (a) primary azimuthal gap and (b) secondary azimuthal gap obtained from a Monte Carlo simulation of relocating the 1999 November 11 Dead Sea calibration explosion and the 1992 November 2 ammunition storage explosion in Switzerland with 10 randomly selected stations within 250 km from the epicentre.

of far-field waveforms for this event (Barker *et al.* 1999) tends to complicate phase picking, perhaps making this explosion more similar to earthquakes than many nuclear tests. 10 000 free-depth locations were computed by randomly selecting between 10 and 70 stations (out of 125) in the teleseismic distance range. The 2-D histogram of mislocation versus secondary azimuthal gap (Fig. 12a) suggests that the 120° secondary azimuthal gap criterion is a reasonable choice. The cumulative distribution of mislocations (Fig. 12b) for realizations located with secondary azimuthal gap of less than 120° confirms the $\mathrm{GT25}_{90\,\mathrm{per\,cent}}$ criterion determined for the earthquake population discussed above (Fig. 11b).

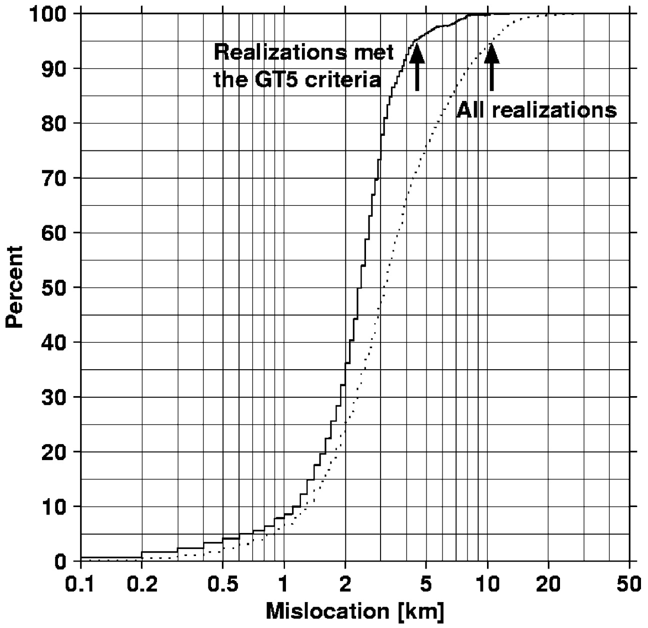

Figure 7. Cumulative percentile plots of mislocations showing all realizations (dotted line) and those satisfying the $\mathrm{GT}_{95\,\mathrm{per\,cent}}$ local network location accuracy criteria (solid line). The worst mislocation for events identified by the location accuracy criteria is 10 km. The arrows indicate the mislocation at the 95 per cent confidence level.

Considering mislocation accuracy as a function of the number of stations for the Pakistani nuclear test, we find that accuracy steadily improves up to approximately 25–35 stations, but then stays almost constant with increasing numbers of stations (Fig. 13a). We suspect that once the number of stations necessary to fulfil the secondary gap criterion is reached, adding more stations does not significantly improve network coverage and negative factors, such as correlated path anomalies and non-zero average traveltime prediction errors counteract any improvement from greater numbers of readings. The location accuracy also shows a slight, almost linear dependence on estimated focal depth (Fig. 13b). A depth error of 100 km is required to cause a 25 km location error, on average.

4 DISCUSSION

The criteria we have established here provide a means of estimating epicentre error which will err on the generous side, in that they assume no special efforts have been made to remove location bias through traveltime calibration or application of the most recent algorithms. Detailed studies, such as the use of optimized 1-D models or the use of 3-D Earth models, may significantly improve location accuracy. Better models not only improve traveltime prediction accuracy, but they more closely satisfy the assumption that traveltime prediction errors are unbiased. Furthermore, arrival-time reading errors can be reduced through careful analysis of traveltime residuals for event clusters, review of waveforms, and determination of relative arrival times based on waveform correlation. Also, advanced location algorithms, such as multiple event location techniques (Douglas 1967; Jordan & Sverdrup 1981; Pavlis & Booker 1983; Dewey 1991; Waldhauser & Ellsworth 2000; Engdahl & Bergman 2001; Rodi & Toksöz 2001), can improve the accuracy of seismic locations. However, our goal is to establish location accuracy criteria for routine catalogue locations for which no specialized studies have been made.

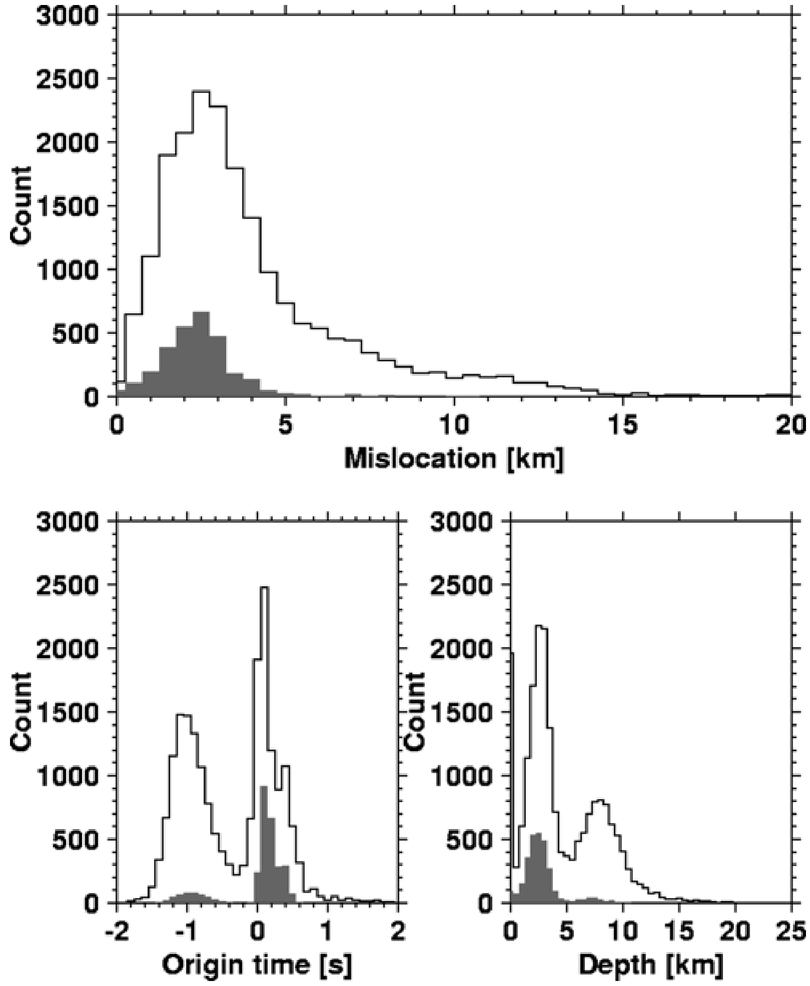

Figure 8. Distributions of (a) mislocation, (b) origin time and (c) depth for all realizations (solid lines) and for the realizations that meet the GT$_{95\,\mathrm{per\,cent}}$ local network location accuracy criteria. The criteria effectively cut-off the heavy tails of the distributions.

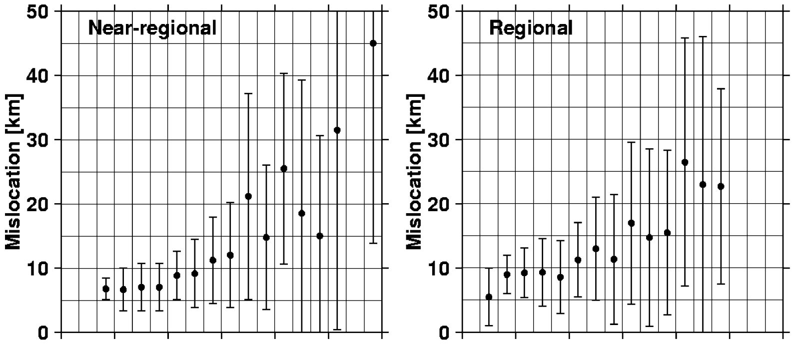

Figure 9. Median of mislocation versus secondary azimuthal gap for all test events, for (a) near-regional (2.5°–10°) and (b) regional (2.5–20°) distance ranges. Near-regional networks consistently perform better than regional ones, indicating that data from far regional stations may often degrade location accuracy.

4.1 Explosions versus earthquakes

As we noted earlier, there is a significant difference in location accuracy between earthquakes and explosions at known test sites. At regional distance the same network-coverage criteria results in GT15$_{95\,\mathrm{per\,cent}}$ location accuracy for explosions and GT20$_{90\,\mathrm{per\,cent}}$ for earthquakes. At teleseismic distances GT15$_{95\,\mathrm{per\,cent}}$ degrades to GT25$_{90\,\mathrm{per\,cent}}$ for earthquakes.

A number of factors may contribute to the location accuracy discrepancy between earthquakes and nuclear explosions.

(1) Earthquake waveforms tend to be complicated by source finiteness, complexity and radiation patterns compared with the typically clear, impulsive arrivals of nuclear shots. Waveform complexity results in larger average picking error for earthquakes.

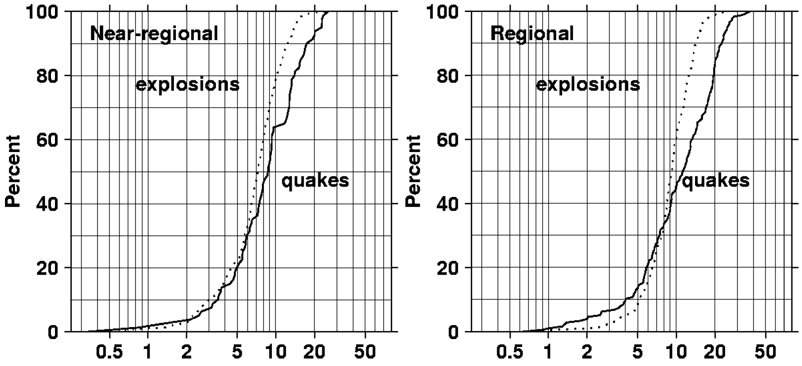

Figure 10. Cumulative percentile plot at 5 per cent intervals for mislocations of earthquakes (solid line) and explosions (dotted line) for events with secondary azimuthal gap of less than 120°, for (a) the near-regional distance range (2.5–10°) and (b) the regional distance range (2.5–20°). For the near-regional case, approximately 80 per cent of the explosions with secondary azimuthal gap of less than 120° have mislocations of 10 km or less.

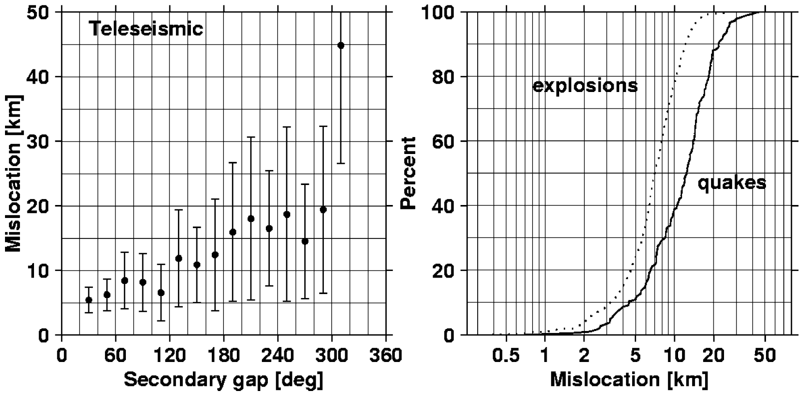

Figure 11. (a) Median mislocation versus secondary azimuthal gap for all test events for the teleseismic distance range (28–91°). (b) Cumulative percentile plot for mislocations of earthquakes (solid line) and explosions (dotted line) for events with secondary azimuthal gap of less than 120°, for the teleseismic distance range (28–91°).

(2) Nuclear explosions at known test sites receive detailed analyst review. Furthermore, the sharp peak in the residual distribution at zero (Figs 3b–d) suggests that many readings for nuclear explosions at known test sites are guided by theoretical traveltime curves, yielding very consistent (albeit false) readings.

(3) Locations of our earthquake reference events (typically GT5 or better) are not as accurately known as the locations for our explosion reference events (typically GT2 or better). Assuming a randomly oriented mislocation vector, the use of GT5 adds a small (perhaps 1–2 km) static baseline shift to the mislocation statistics of the earthquake population.

(4) Earthquakes tend to occur in tectonically active—thus more heterogeneous—regions. The effect would be additional bias in locations.

(5) There is greater uncertainty concerning the depths of our earthquake reference events. Nuclear explosions are generally fixed within 1–2 km of the surface. Depth errors for the earthquakes may be correlated with epicentre errors. Fig. 13b suggests that this effect is probably very minor.

(6) Some subduction zone events are included in the earthquake data set and these may contribute disproportional location bias.

Although each of these factors may diminish the location accuracy for earthquakes, Fig. 3 suggests that analyst attention to nuclear explosions may be the dominant factor. In each distance range the statistical mode (the peak of the distribution) of the traveltime residuals was significantly closer to zero for explosions than for earthquakes, suggesting that *a priori* information on expected arrival times aided in phase identification. The bimodal shape of the explosion residuals is striking. Specifically, we suspect that many analysts, knowing that they were looking at a seismogram from a shot at a known nuclear test site, made their picks with the undue aid of theoretical traveltime tables.

If this hypothesis is true, criteria for estimating location accuracy for earthquakes should not be based on data for test-site explosions.

Although many arrival-time picks for nuclear explosions appear to be aided by predicted traveltimes, the shoulders in the explosion residual populations for near-regional and regional distances indicate the presence of systematic path anomalies (such as slower propagation to Californian stations from the Nevada Test Site, and faster propagation through the Russian platform from Novaya Zemlya and Semi-palatinsk). The signature of systematic path anomalies is not as evident in the earthquake residual population because a greater diversity of anomalous ray paths (from many more source regions) smears out the distribution and the reduced location accuracy of earthquakes in the GT5 data set adds to the variance of the distribution.

4.2 Depth and origin time

For many applications event depth and origin time are as important as the epicentre. However, unlike epicentre parameters, depth and origin time estimates are strongly dependent on the velocity

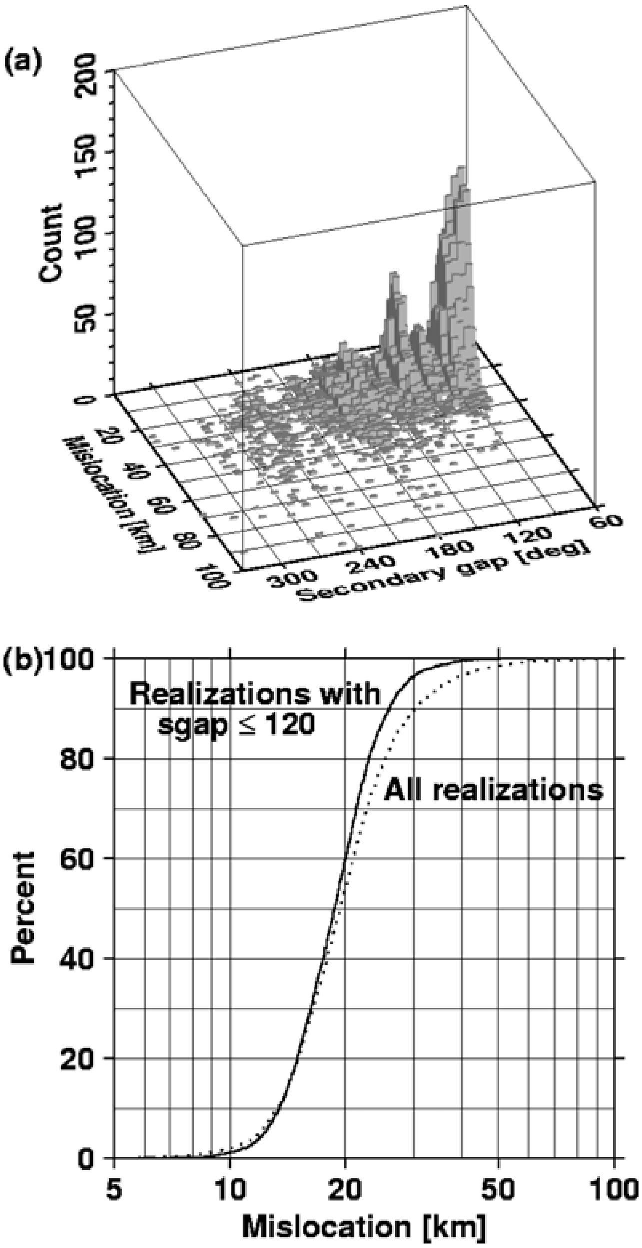

Figure 12. Monte Carlo simulation of teleseismic networks using the 1998 May 28 underground nuclear explosion in Pakistan. (a) Histogram of mislocation versus secondary azimuthal gap, (b) cumulative percentile plot of mislocations showing all realizations (dotted line) and those with secondary azimuthal gap of less than 120° (solid line).

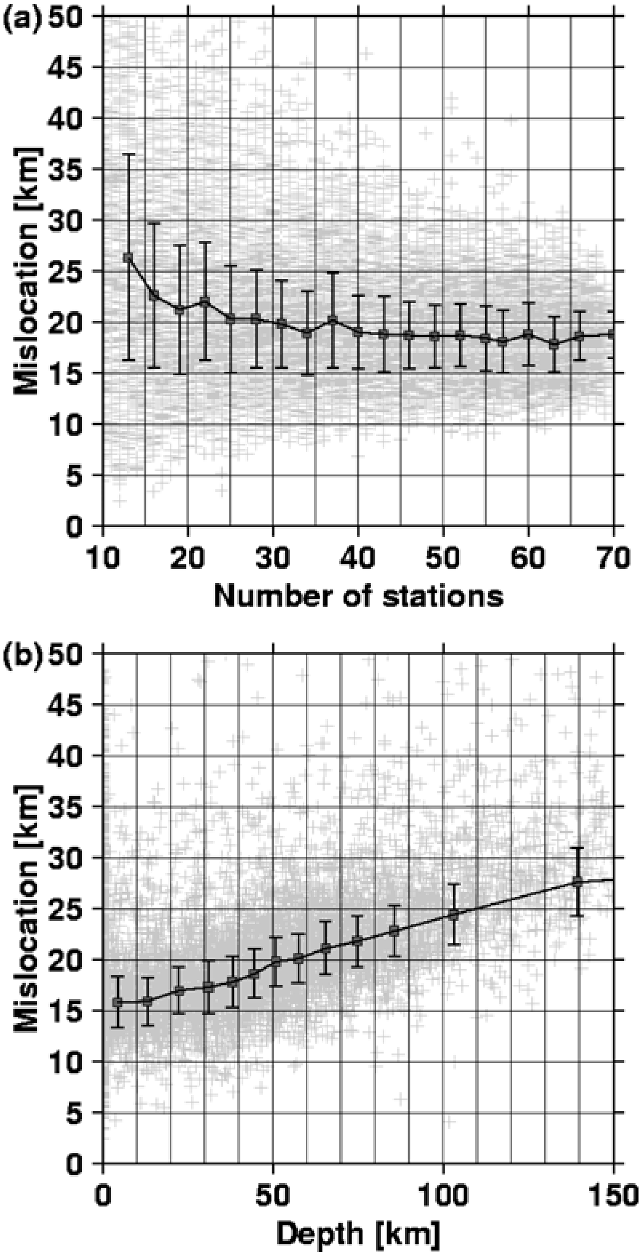

Figure 13. Mislocation of the 1998 May 28 underground nuclear explosion in Pakistan as a function of (a) number of stations and (b) depth for teleseismic networks obtained from the Monte Carlo simulation. In each case the median and spread are plotted for each 5 percentile worth of data, using all realizations.

model, hindering the development of network-geometry-based accuracy criteria.

We use the geometry of the Racha, Georgia aftershock sequence (Fuenzalida *et al.* 1997) to test the sensitivity of velocity model error on local-network location errors (after, Myers & Schultz 2000b). We generate synthetic arrivals using a simple velocity model, then perturb the velocity model and relocate the events (Fig. 14). We see that for this realistic network geometry, epicentre accuracy is maintained, with mislocation of only approximately 0.5 km (when only *P*-waves are used). However, bulk velocity model error can shift depth estimates by up to 5 km and origin time-shifts can exceed 0.6 s. We find that inclusion of S-arrivals reduces the origin time and depth error, but degrades epicentre accuracy, although depth and origin time errors remain larger than epicentre errors.

Estimation of the focal depth based on phase arrival times from regional and teleseismic networks is difficult at best. Focal depth is poorly constrained by direct phases in these distance ranges. Fig. 15 shows that traveltime residuals are relatively insensitive to large changes in event depth, when compared with other location parameters (Myers & Schultz 2000b). Because residual sensitivity to depth error is distance dependent, depth accuracy criteria should be based on the coverage of event-station distance range. However, we do not establish such a criteria here, because we do not have ground-truth

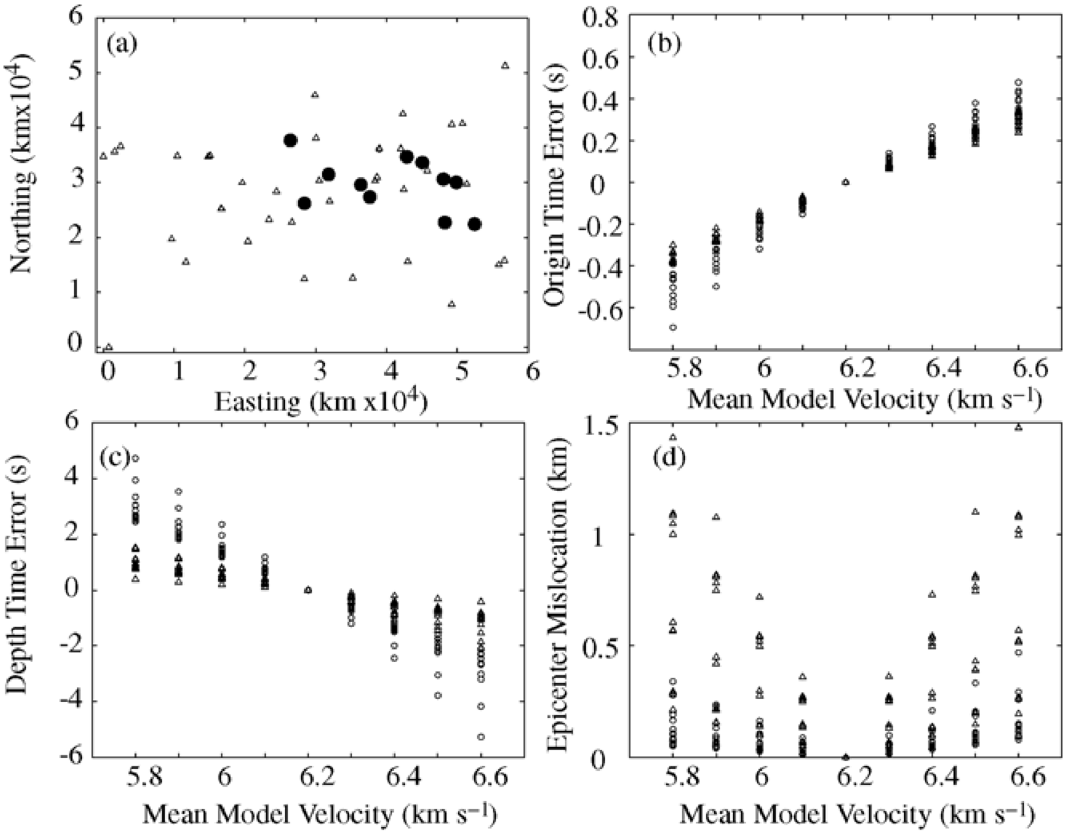

Figure 14. Simulation of the Racha aftershock sequence using the true network geometry to test the sensitivity of local-network locations to velocity model error. For 11 events with excellent network coverage, we generate synthetic arrival times for *P* and *S* phases using a velocity model with bulk *P*-wave velocity of 6.2 km s^{-1} ($V_p/V_s = 1.73$). We then change the bulk velocity and relocate the events. (a) The network coverage is excellent for our test cases; triangles are seismic stations. (b)–(d) Origin time, depth and epicentre errors for relocations using only *P*-waves (circles) and *P*- and *S*-waves (triangles), respectively (see the text for discussion).

data (i.e. very accurate depth control for events recorded at regional and teleseismic distances) to validate the approach.

Although arrival times of surface-reflected phases (e.g. *pP*, *sP*) can be used to improve depth estimation, surface-reflected phases for events in the shallow crust (and *pwP* in the case of suboceanic events) are commonly convolved into one group arrival, complicating analyst efforts to pick phase onsets. As a result of these complications, depth phases are reported for only half of all ISC events, including deep events. Even when surface-reflected arrivals are clear, phase identification can be problematic. Engdahl *et al.* (1998) find that re-identification of these phases (for events at all depths) based on a probabilistic model of arrival times significantly improves catalogue consistency, suggesting that surface-reflected phases are often misidentified. Moreover, a large number of phases reported by the ISC with no phase identification could be associated as depth phases or *PcP*.

We note that even when surface-reflected phases are used to constrain depth, origin time is still poorly resolved due to the dependence on traveltime prediction error. If depth phases (*pP*, *sP*) or reflected phases (*PmP*, *PcP*) are not used to constrain depth, then depth and origin time error are almost perfectly correlated and the accuracy of neither parameter can be assessed.

5 CONCLUSIONS

A wide variety of seismic studies (seismic hazard analysis, regional and teleseismic tomography to derive 3-D velocity models of the Earth, and location calibration) depend on commonly available earthquake catalogue locations. All such studies must make assumptions concerning the accuracy of those locations, but we have shown that, in general, the uncertainties for standard catalogue locations are unreliable and generally optimistic. Recognizing the need to establish location accuracy criteria based on bulletin data, we establish criteria for assessing epicentre accuracy. We also recognize the importance of event depth and origin time. However, event depth and origin time accuracy are linked to traveltime prediction accuracy, which depends on the accuracy of the velocity model used to develop the catalogue. Since the quality of the velocity model is difficult to assess from the catalogues themselves, we did not attempt to develop criteria for the general assessment of accuracy of depth and origin time.

We identified four distance ranges: local (0°–2.5°), near-regional (2.5°–10°), regional (2.5°–20°) and teleseismic (28°–91°) for which reliable criteria can be developed. These distances are chosen because traveltime prediction and phase picking uncertainties are distinct in each range.

We used events with GT0 location accuracy to develop and validate GT5$_{95\,\mathrm{per\,cent}}$ criteria for local network locations. We used a large set of very well located earthquakes and nuclear explosions with uncertainties of GT5 or better to develop location accuracy criteria for regional and teleseismic distance ranges. In regional and teleseismic distance ranges, location accuracy for earthquake and explosion populations is quite distinct. We find that for any level of station coverage, earthquakes are not as well located as

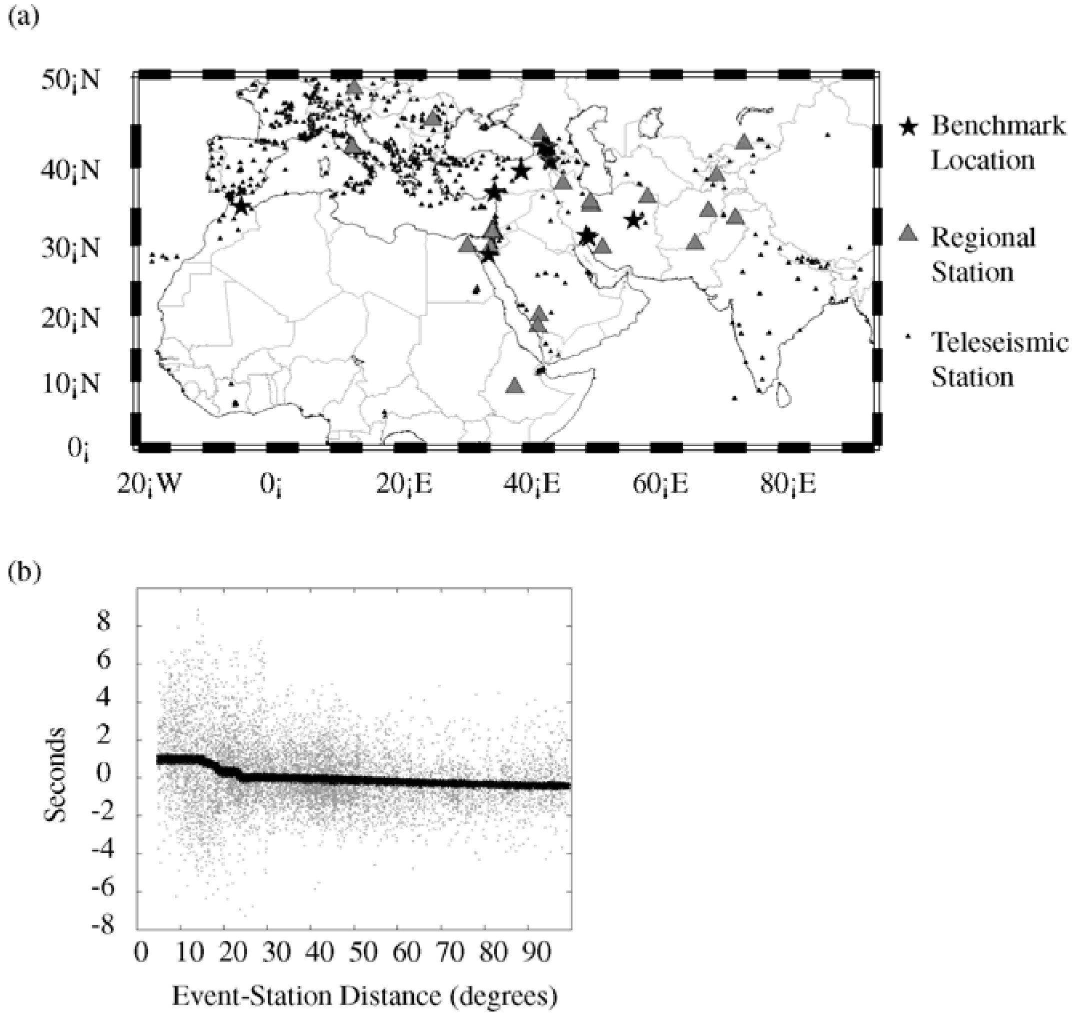

Figure 15. Traveltime residuals resulting from errors in event depth are compared with the overall residual spread. (a) Benchmark epicentre locations (stars) are determined with local networks (aftershock deployments). Epicentres are fixed at the local-network locations to minimize errors due to lateral mislocation. Origin time is determined for depths of 0 and 30 km using teleseismic *P*-wave arrivals (small triangles are teleseismic stations). (b) The difference in traveltime residuals for 0 and 30 km depths (black) are plotted with the residual population for 0 km depth locations (grey). Residual error caused by a 30 km change in depth is difficult to resolve when viewed against the overall residual spread. The small change in traveltime residual with large changes in event depth shows the difficulty of determining depth (see the text for discussion).

explosions, and the difference in accuracy is approximately 5–10 km.

We find evidence that a large fraction of reported readings for nuclear explosions at established test sites have been made with undue reliance on theoretical traveltimes. Therefore, using GT0 nuclear explosions at established test sites to derive location accuracy criteria for earthquakes would lead to overly optimistic results. To avoid this problem, we used a well-located data set of GT5 earthquakes to establish location accuracy criteria for earthquakes at regional and teleseismic ranges. These criteria withstand further validation using the 1998 May 28 underground nuclear explosion in Pakistan, which has many of the characteristics (including an unknown location when most readings were made) of an earthquake for this purpose.

The location accuracy criteria derived here are most relevant to continental earthquakes. Subduction zone events are likely to have a larger (and systematic) location uncertainty due to the traveltime bias introduced by the subducting slab, even if the station coverage satisfies the location accuracy criteria.

The location accuracy criteria given below assume that no special effort has been made to remove location bias through the use of an optimal velocity models or traveltime corrections, or through special analysis of waveforms or readings to improve phase readings.

The epicentre accuracy criteria for earthquakes in the various distance ranges are given below.

(1) Local networks (0°–2.5°). At least 10 stations, all within 250 km; these 10 stations should have an azimuthal gap of less than 110° and a secondary azimuthal gap of less than 160° and at least one station should be within 30 km. These criteria provide a location accuracy of $\mathrm{GT5}_{95\mathrm{percent}}$.

(2) Near-regional networks (2.5°–10°). Secondary azimuthal gap of less than 120° results in location accuracy of $\mathrm{GT20}_{90\,\mathrm{per\,cent}}$.

(3) Regional networks (2.5°–20°). Secondary azimuthal gap of less than 120° results in location accuracy of $\mathrm{GT25}_{90\,\mathrm{per\,cent}}$.

(4) Teleseismic networks (28°–91°). Secondary azimuthal gap of less than 120° results in location accuracy of $\mathrm{GT25}_{90\,\mathrm{per\,cent}}$.

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