ESTABLISHING AND VALIDATING EMPIRICALLY-BASED GROUND TRUTH CRITERIA FOR SEISMIC EVENTS RECORDED ON REGIONAL NETWORKS

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ABSTRACT

We have extended the approaches of Bondár et al. (2004), Bondár and McLaughlin (2009), and Boomer et al. (2010) by developing new empirically based ground truth (EBGT) local criteria for a variety of geologic settings for which data sets containing *GT0* events (explosions and mine tremors) are available, local crustal structure is well known, and hand-picked arrival times have been obtained. Boomer et al. (2010) describes the development of local criteria for the simple crustal structure of the Archean Kaapvaal Craton in southern Africa. Continuing the development of local criteria in regions of varying geologic complexity, we now have criteria for the Main Ethiopian Rift and preliminary criteria for the Tibetan Plateau.

In the geologically very complex region of the Main Ethiopian Rift, we use the 2003 Ethiopia-Afar Geoscientific Lithosphere Experiment (EAGLE; Maguire et al., 2003) data to obtain $EBGT5_{95\%}$ criteria. Four of the 25 large refraction line shots were used as reference events to develop the criteria; the remainder was used as verification shots. We require an event to be recorded on at least 8 stations within the local the Pg/Pn crossover distance and a network quality metric (Bondár and McLaughlin, 2009) less than 0.43 for an event to be classified as $EBGT5_{95\%}$. Using these criteria to identify GT events within the Ethiopian Broadband Seismic Experiment, we have identified ten events to add to the NNSA knowledge database. In addition, there is a set of 196 potential GT events for the EAGLE dataset, and from this set we expect to obtain up to 20 new GT5 events.

The crust and upper mantle structure of the Tibetan plateau is arguably more complicated than for the Kaapvaal Craton yet less complicated than the Main Ethiopian Rift, and includes a number of prominent suture zones. Five of the 11 larger shots from the International Deep Profiling of Tibet and the Himalaya (INDEPTH III) refraction line were used to develop the criteria. The remaining 6 shots will be used to validate the criteria. The preliminary criteria for Tibet are similar to the Ethiopian criteria, yet slightly less restrictive as the network quality metric needs to be less than 0.45. If confirmed, there are 126 potential events from Tibet that will most likely yield about 10 $EBGT5_{95\%}$ events. As the complexity of geologic structure increases from craton, plateau to rift our criteria show increasing restrictions in the network quality metric.

OBJECTIVES

Determining accurate seismic locations with representative uncertainty estimates is of fundamental importance to ground-based nuclear explosion monitoring, including the assignment of accurate ground truth (*GT*) levels. The monitoring community relies on selection criteria for classifying seismic events at the *GT*5 level, which specifies the absolute location and depth errors as being less than 5 kilometers. Regional-network locations are currently validated at the $GT20_{90\%}$ level, which does not satisfy the requirement for $GT5_{95\%}$ validation for inclusion in the NNSA Knowledge Base.

Our recent work testing the existing global *GT* criteria against *GT0* mine events in southern Africa recorded on a sparse regional network shows that the global *GT* criteria (Bondár et al., 2004; Bondár and McLaughlin, 2009) presently used by the community may be overly restrictive in some regions, at least for regions with relatively homogeneous crustal and upper mantle structure (Boomer et al., 2010). Consequently, there are likely many *GT5* events recorded by regional networks that do not appear in *GT5* catalogs, including events in strategically important areas.

The objective of this project is to develop new criteria for acquiring location ground truth from regional networks that both account for the complexities in Earth structure beneath a network, and the fact that through careful phase picking, high quality travel time measurements can be obtained. Empirically based ground truth (EBGT) criteria have been developed for the Main Ethiopian Rift and the Tibetan Plateau, which are both regions with more complex structures than southern Africa.

The *EBGT5* criteria for these two regions, when combined with the criteria already obtained for the Kaapvaal Craton, will enable us to compare regionally-developed criteria against the existing global criteria for a range of tectonic settings (i.e., stable craton, plateau within a collisional zone, and an active rift). We anticipate that as the level of heterogeneity in the geologic structure increases, at some point the regional *EBGT* criteria will become similar to the global 2004 and 2009 criteria. Now that the *EBGT* criteria appropriate for each tectonic setting has been established, in the second part of this project we will apply them to several datasets from eastern Turkey, the Arabian Peninsula, the Tibetan Plateau, and Kyrgyzstan with the goal of identifying new *GT5* events. In addition, we will use a correlation method between observed and synthetic seismograms to improve the precision of the arrival time measurements, thus further improving the location accuracy of the events we anticipate adding to the *GT5* catalog.

RESEARCH ACCOMPLISHED

The deliverables for the first year of this project include the development of *EBGT5* criteria for the Main Ethiopian Rift and the Tibetan Plateau.

Geological Background and Data Sources

The Main Ethiopia Rift is geologically very complex, and the well-determined crustal and upper mantle studies from several seismic investigations have revealed heterogeneity in structure both across and along the rift. We are using the data set from the 2003 Ethiopia-Afar Geoscientific Lithosphere Experiment (EAGLE; Maguire et al., 2003) to obtain *EBGT5* criteria for this rift. The data set includes a combined active-passive source seismic experiment, where 25 large shots were well recorded across the refraction profiles as well as by a local/regional network of 80 broadband stations (see Figure 1). Arrival times from these shots were provided by Keranen et al. (2004). Station dependant velocity models were adapted from EAGLE refraction studies (Maguire et al., 2006) and receiver function models from Dugda et al. (2005). In addition, Keir et al. (2006) provide a seismicity study of the rift using the broadband stations, listing over 2000 local events; the Ethiopian Broadband Seismic Experiment recorded over 400 local and regional events on 25 broadband seismic stations between 1999 and 2001 (Brazier et al., 2008).

The Tibetan Plateau resulted from a continent-continent collision between the Indian and Eurasian plates, creating an uplifted region (5km of topography in places) 550-1200 km wide with crustal thickening of up to ~70km. The crust and upper mantle structure of the plateau is arguably much more complicated than for the Kaapvaal Craton, and includes a number of prominent suture zones. The INDEPTH III project conducted a 400km long active-passive seismic project that recorded more than 50 shots (Table 1). Eleven shots had charge sizes ranging from 180 to 1160 kg, which we are using to develop local criteria. At the conclusion of the active-source experiment, many broadband stations remained in place to record naturally occurring seismic events (Figure 2).

Langin et al. (2003) provide a seismicity study of the local and regional events recorded by the project and a catalog of 267 local and regional events, many of which have magnitudes larger than 3. The events were located using a 1D velocity model of the crust and upper mantle derived from the refraction profiles.

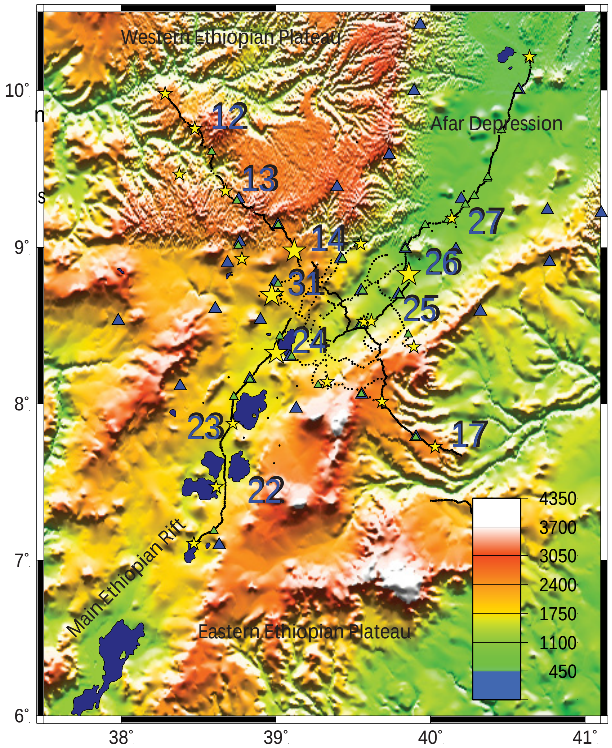

Figure 1. Map of central Ethiopia showing the location of broadband stations (blue and green triangles) and shotpoints (yellow stars) from the January, 2003, EAGLE project.

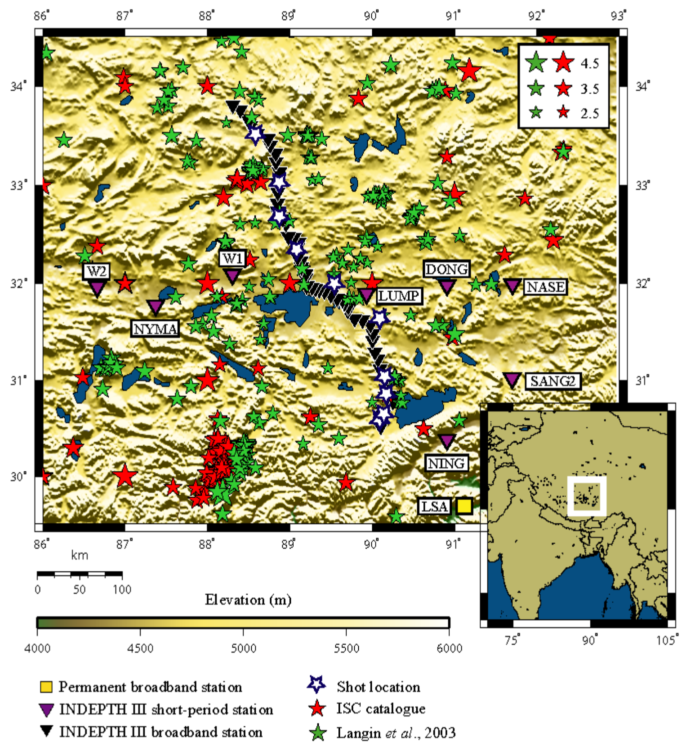

Figure 2. Maps showing local and regional seismicity from the INDEPTH III project in Tibet.

Bondár et al. (2004) explore the use of network coverage as a metric for assessing location accuracy. In their work, network coverage was quantified by measuring not only the primary but also the secondary azimuthal gap. By restricting the primary gap to less than 110° and the secondary gap to less than 120° (160° for local networks), selection criteria (see Table 1) were developed to classify an event location as being accurate within 5 km (or 20 km, locally) with 95% (or 90%) confidence ($GT5_{95\%}$, $GT20_{90\%}$, respectively). As these criteria are based on the global *Pg/Pn* crossover distance of 250 km, they may not be representative of the local velocity structure and thus may lead to phase identification errors.

In 2009, Bondár and McLaughlin modified the selection criteria using a 150 km *Pg/Pb* crossover to relocate over 90 *GT*0 reference events, in part to address the concern over phase identification errors (Table 1). A new network quality metric DU was introduced as a means to assess the uniformity of azimuthal coverage. This metric is similar to the Kolmogorov-Smirnov test of whether the station azimuths are uniformly distributed in a circle around the epicenter. Bondár and McLaughlin found that networks with values of DU less than 0.35 tend to provide *GT*5 candidates. As with the 2004 selection criteria, these modified criteria were developed using events recorded on a large number of local and regional recording stations with travel times reported in bulletins. Bondár and McLaughlin (2009) also simulate sparse networks and select the 20 most representative network geometries in developing their modified criteria.

Using a local *Pg/Pn* crossover distance of 215 km, Boomer et al. (2010) develop *EBGT* criteria for the Kaapvaal Craton. Networks with a primary gap greater than 202° yielded mislocations in excess of 40 km, which were considered to be obvious outliers. Further, due to the homogeneous crustal structure, secondary gap did not provide additional constraint. Unlike the regions used to develop the 2004 and 2009 criteria, the Kaapvaal Craton was measured with a sparse network, with some of the larger mine-related events (e.g., *GT*0 events) recorded on 16 or fewer stations.

Table 1: Existing epicentral location accuracy criteria

Network	Distance Range (degrees)	Primary Azimuthal Gap	Secondary Azimuthal Gap	Number of stations within specified distance			GT level
				Between Pg/Pn crossover and 1000km	< Pg/Pn Crossover	minimal distance	
Local[a]	0°-2.5°	110°	160°		10	1 within 30km	$GT5_{95\%}$
Near Regional[a]	2.5°-10°		120°	10			$GT20_{90\%}$
Teleseismic[a]	28°-91°		120°				$GT25_{90\%}$
Kaapvaal EBGT[b]	0°-1.9°	202°			8	1 within 79 km	$GT3_{95\%}$
Network	**Distance Range (degrees)**	**Network Quality Metric ΔU**		**Between Pg/Pb or Pg/Pn crossover and 1000km**	**< Pg/Pn (< Pg/Pb) Crossover**	**< 10km**	**GT level**
Local[c]	0°-1.35°	< 0.35			5	1 within 10 km	$GT5_{95\%}$
Ethiopia EBGT[d]	0°-1.6°	< 0.43			8		$GT5_{95\%}$
Tibet EBGT[d]	0°-3.3°	< 0.45			8	1 within 65 km	$GT5_{95\%}$

Notes: [a]Bondár *et al.* 2004
[b]Boomer *et al.* 2010
[c]Bondár and McLaughlin, 2009
[d] This report

The re-sampling method often used in developing selection criteria (e.g. Bondár et al., 2004; Yang et al. 2006; Bondár and McLaughlin, 2009) is bootstrapping in which $k \le n$ arrival times are sampled with replacement from the set of n available arrival times. Sampling with replacement is used to ensure independent samples, and, particularly when there are a large number of possible elements (e.g., arrival times), a large number of realizations can easily be achieved. The EBGT Kaapvaal Craton criteria were developed using a similar statistical re-sampling technique, the jackknife method. This approach considers all possible subsets of the $k \le n$ arrival times, permitting the determination of criteria based on the number of recording stations with a smaller number of arrival times.

Empirically Based Ground Truth Criteria for the Tibetan plateau

We have developed preliminary EBGT criteria for the Tibetan Plateau using data from shot points (SP) 6,7,8,9 recorded on up to 54 stations, 44 in the refraction profile and ten cross profile or permanent stations (Figure 2). Arrival times and station dependent velocity models were adapted from Zhao et al. (2001). With around 40 arrival times for each shot, we are able to use a bootstrap resampling method. Three bootstrap samples, each based on 10,000 realizations of n = 7, 8 or 9 arrival times, were analyzed. Networks are quantified based on a maximum and minimum epicentral distance, and the network quality metric ΔU.

The criteria obtained (Table 1) require that the maximum epicentral distance be less than 3.3 degrees, which is the local *Pg/Pn* crossover distance and an epicentral distance to the closest station of less than 65km. Relocations with a station within 65km show no relationship to epicentral change or depth, however, greater than 65km were not able to constrain the depth. Scatter plots and the empirical cumulative distribution functions in Figure 3 demonstrate that the estimated mislocation error is less than 5km, with 95% confidence, when $\Delta U < 0.45$ for events recorded on eight stations. In addition the depth mislocation error is less than 8km, and origin time error less than 0.8 seconds.

The six remaining shots in the Tibet dataset with charge sizes greater than 180kg will be used to verify the criteria. Based on the criteria in Table 1, there are more than 126 potential events with $M \geq 2.5$ in the Tibetan data set that we can relocate and add to the GT5 catalog.

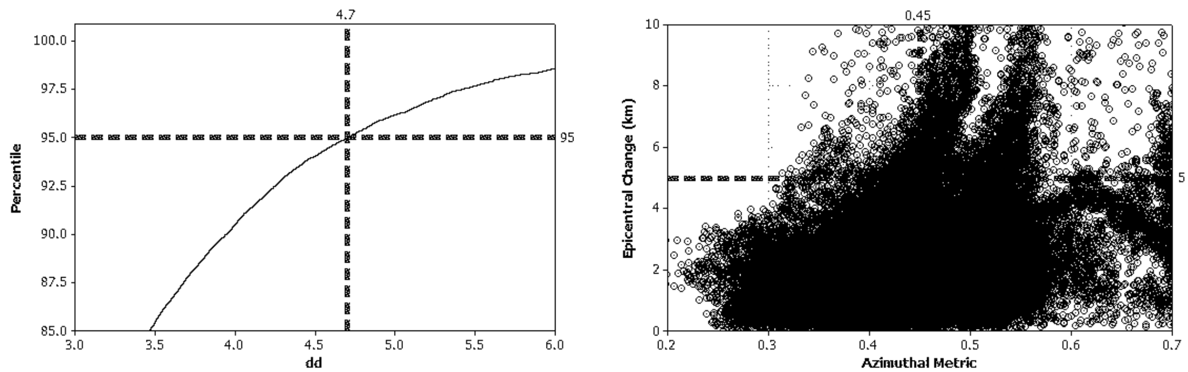

Figure 3. (Left) Empirical Cumulative Distribution Function demonstrates that the 95th percentile of epicentral change is less than 5km. (Right) The scatterplot of the absolute change in epicentral change versus ΔU shows that an epicentral change < 5 km corresponds to $\Delta U < 0.45$ with 95% confidence.

Empirically Based Ground Truth Criteria for the Main Ethiopian Rift

$EBGT5_{95\%}$ criteria have been developed for the Main Ethiopian Rift using four explosions (SP14, SP24, SP26, SP31) located centrally in the EAGLE array (Figure 1). The shots were recorded on up to 32 EAGLE broadband stations and over 600 stations in the refraction lines within the local *Pg/Pn* crossover distance. Three bootstrap samples for each shot, based on 10,000 realizations of n = 7, 8 or 9 arrival times from the refraction line stations, were used to develop these criteria. Networks were quantified based on maximum epicentral distance and the network quality metric ΔU.

The criteria obtained require that the maximum epicentral distance be 1.6 degrees or less, which is the local *Pg/Pn* crossover distance, and that $\Delta U < 0.43$ (Table 1). Once the azimuthal constraint is applied all minimum epicentral distances are less than 100km, there is no discernable relationship between depth and minimum distance, no additional constraint is applied. The empirical cumulative distribution function and scatterplot in Figure 4 demonstrate that the estimated mislocation error is less than 5km, with 95% confidence, when $\Delta U < 0.43$. In addition, the depth mislocation error is less than 11km, and origin time error less than 1.8 seconds. We verified the criteria using data from the four shots recorded on stations that were not part of the broadband stations used in the criteria, along with data from 10 other shots recorded on non-broadband stations.

Using the criteria, we have identified 10 events from the Ethiopian Broadband Seismic Network (Table 2) and 196 events from the EAGLE dataset that could potentially meet the $EBGT5_{95\%}$. After event relocation, we expect that many of those events can be added to the GT5 catalog.

Table 2: Ethiopia Broadband Seismic experiment events meeting the Ethiopia EBGT5$_{95\%}$ criteria

Date	Time	Lat.	Lon.	Dep.	N	Dist.	Gap	RMS	Mag	Metric
5/12/2001	2:06:42	9.4984	39.7118	0.03	8	28	62	0.3295	2.8	0.13
5/23/2001	1:16:10	9.4611	39.4401	1.72	10	25	95	0.39	3.6	0.18
6/15/2001	0:19:24	8.3794	38.6859	35.92	7	44	136	3.6028	2.5	0.38
11/2/2001	23:04:25	9.4785	39.6956	5.75	8	28	82	0.2433	2.2	0.33
11/11/2001	21:05:23	9.5617	39.5127	0	9	12	73	5.1336	2.2	0.17
11/11/2001	22:32:43	9.462	39.6982	11.18	8	30	84	0.3925	3.1	0.14
11/11/2001	22:38:03	9.4443	39.7032	0.05	8	32	84	0.5243	3.8	0.13
11/11/2001	23:35:45	9.4705	39.716	0.1	7	31	83	0.7221	2.2	0.12
11/27/2001	21:35:37	9.4986	39.6886	17.36	9	26	66	0.7404	2.5	0.2
12/13/2001	2:14:40	9.4639	39.6881	1.89	8	29	85	0.4401	3.1	0.14

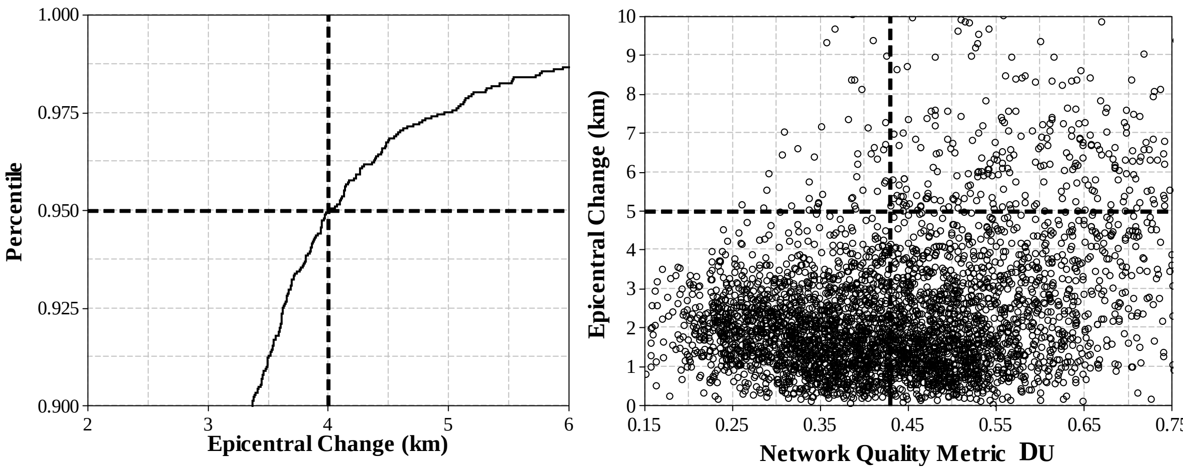

Figure 4. Ethiopian local EBGT5$_{95\%}$ criteria are based on the cumulative distribution function for epicentral change (95th percentile at 4 km) and a network quality metric ΔU < 0.43

Exploring additional spatial metrics to assess network quality

A basic premise of recent work in developing GT criteria is that network geometry influences event location, with greater coverage yielding more accurate locations. Developed criteria have a stated range of epicentral distances and a measure of azimuthal coverage, either in terms of azimuthal gap or the network quality metric. We are interested in describing network geometry in terms of both azimuthal coverage as well as the distribution of epicentral distances. This is an important aspect of developing local and regional criteria in areas with heterogeneous crustal structures; in an extreme case, a network could satisfy existing criteria by having adequate azimuthal coverage yet have all stations with the same epicentral distance (with the exception of one station within the stated minimal distance). Such a configuration may lead to unrepresentative arrival times for the region.
In addition, metrics based primarily on azimuthal coverage suffer when there is more than one station with the same azimuth, yet with different epicentral distances. This is especially problematic when analyzing data along a refraction line. In developing the local Tibet EBGT criteria, one event was recorded close to the center of the refraction line. Despite being recorded on 58 stations on the refraction line, many had the same azimuth. As a result, only 18 stations had unique azimuths.

We are interested in spatial metrics that describe the two dimensional coverage of a network within the Pg/Pn crossover distance; early work using the bootstrap samples from Ethiopia have considered the sum of nearest neighbors and the area of the polygon formed by the network. Both measures capture the dispersion of network stations in ways that metrics based on azimuthal uniformity do not.

Figure 5 shows boxplots for the sum of nearest neighbors in a network, for bootstrap samples which meet *EBGT5* criteria, those that do not, and for arrays generated to represent complete spatial randomness (CSR). Larger values of this metric indicate more disperse networks. Using the lowest 0.05 percentile from the CSR distribution to representing the most compact networks (ΣNN<4), 77% of the *GT5* networks and 90% of the networks with GT >5km are more clustered than we would expect under CSR. While the physical placement of stations is not a spatial point process (e.g. physical constraints limit areas in which stations can be placed), this preliminary result suggests spatial methods may be able to discriminate between networks that are or are not likely to meet *GT5* criteria.

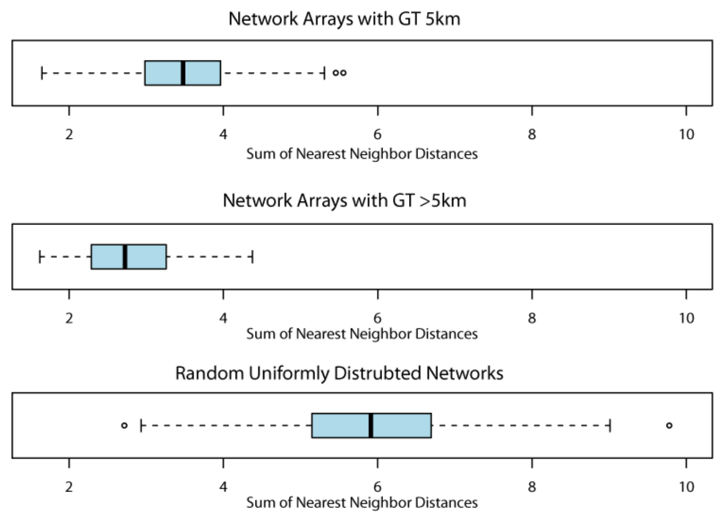

Figure 5. Early developments using a spatial metric to characherize networkds indicate some ability to discriminate between networks that do and do not meet GT5 criteria.

To what degree are region-specific EBGT transferable to other regions?

As the complexity of geologic structure increases from craton, plateau to rift our criteria show increasing restrictions in the network quality metric. The Kaapvaal $EBGT3_{95\%}$ can potentially be applied to other cratonic regions. For example, sixty-one potential events from the Tanzanian Craton and 97 from the Saudi Arabian Shield could be relocated and assessed for GT level using the Kaapvaal criteria as the geological structure is very similar and simple.

As we apply criteria to Eastern Turkey Seismic Experiment (ETSE) and Kyrgystan we will need to assess where these regions sit on the complexity spectrum. At minimum we can use the most conservative (Ethiopian EBGT) to all regions. There is one calibration shot for the ETSE network which is not enough to derive a full criteria but can be used to assess the geological complexity of Eastern turkey.

Comparison of local criteria

The local criteria for southern Africa, Tibet (preliminary), and Ethiopia show that increasing geologic complexity corresponds to increasingly restrictive criteria. Comparing the network quality metric ΔU, we have found that ΔU, $\Delta U < 0.55$ corresponds to the local $EBGT5_{95\%}$ criteria in the Kaapvaal Craton. In Tibet and in the more complex Ethiopian Main Rift, values of the network quality metric of $\Delta U < 0.45$ and $\Delta U < 0.43$, respectively, correspond to local $EBGT5_{95\%}$ criteria. As the network quality metric ranges from 0 (uniform azimuthal coverage) to 1 (stations with the same azimuth), we observe that more uniform coverage is required in more complex regions. In addition, depth and origin time mislocation increase with geological complexity (Table 3).

Azimuthal gap and the network quality metric are purely a result of the station geometry. A network with more uniform coverage within the Pg/Pn crossover distance from an event will yield the greatest information about travel times. As the geologic structure in regions can be classified as more homogeneous, there is less variability in the travel times, and hence station geometries can be somewhat more compact.

Table 3. Comparison of local ground truth criteria

Network	Distance Range (degrees)	Network Quality Metric ΔU	< Pg/Pn (< Pg/Pb) Crossover	Minimal Distance	Depth Mislocation	Origin time Mislocation	GT level
Local[c]	0°-1.35°	< 0.35	5	1 within 10 km			$GT5_{95\%}$
Kaapvaal EBGT[b]	0°-1.9°	< 0.55+	8		5.7km		$GT3_{95\%}$
Tibet EBGT[d]	0°-3.3°	< 0.45	8	1 within 65 km	8km	0.8s	$GT5_{95\%}$
Ethiopia EBGT[d]	0°-1.6°	< 0.43	8		11km	1.8s	$GT5_{95\%}$

CONCLUSIONS AND RECOMENDATIONS

We have developed $EBGT5_{95\%}$ criteria for the Ethiopia Rift and preliminary $EBGT5_{95\%}$ criteria for the Tibetan Plateau. There are ten events from the Ethiopia Broadband Seismic Experiment meeting the appropriate criteria and an additional 196 potential events currently being relocated from the EAGLE dataset. In addition, there 126 potential events from Tibet that once the criteria is verified can also be relocated and added to the NNSA knowledge database. Data from Kyrgystan and Eastern Turkey are being collated ready for determination of potential ground truth events.

The transferability of criteria to other regions is being assessed with the hope that 97 events recorded on the Arabian Plateau can be relocated and included in the database also. As criteria for regions with varying geological complexity are being developed, the azimuthal uniformity constraint needs to be increased with increased geological complexity. In addition it also appears that constraining depth and origin time becomes more difficult as geological complexity is increased.

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