GROUND TRUTH EVENTS FROM REGIONAL SEISMIC NETWORKS IN NORTHEASTERN AFRICA

Andrew A. Nyblade,[1] Richard A. Brazier,[1] Craig Schultz,[2] and Michael Pasyanos[2]

Penn State University,[1] Lawrence Livermore National Laboratory[2]

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ABSTRACT

Determining accurate seismic locations with representative uncertainty estimates is of fundamental importance to ground-based nuclear explosion monitoring. In this project, we are developing a catalog of reference events (ground truth) in the northeast African area of interest where reference event coverage is exceptionally poor due to the limited station coverage by historic networks. We will provide accurately defined hypocenters within a range of ground truth (GT) levels (i.e., GT2, GT5, GT10), origin times, and focal mechanisms for several tens of earthquakes with magnitudes > 3 in northeastern Africa. The catalog will enable the seismic monitoring community to enhance their operational capability to monitor for nuclear tests in North Africa and the Middle East by increasing their ability to accurately locate and identify seismic events in these regions.

The ground truth events for northeastern Africa are being collected using state-of-the-art event location methods applied to broadband seismic data from regional networks in Ethiopia, Kenya, and Tanzania, as well as to broadband data from primary and auxiliary International Monitoring System (IMS) stations in the region. The ground truth catalog is being assembled by (1) determining origin time, focal mechanism and hypocenters with accuracies of 10 km or better (GT 10) for many events that lie within close proximity of recording stations or else are well recorded teleseismically; (2) using these events to construct regional travel-time correction surfaces using a Bayesian kriging technique, and (3) using the travel-time correction surfaces to obtain origin times and epicenters for numerous other events. Robust estimates of the uncertainties in the locations and origin times will also be determined.

Preliminary event locations for many M>4 events in East Africa have been obtained using P and S arrival times recorded by the Tanzania Broadband Seismic Experiment. This experiment consisted of 20 broadband seismic stations deployed across Tanzania in 1994 and 1995. From P and S arrival times, epicentral locations can be constrained to within 2-3 km and focal depths to within 5 km at the 1-sigma error level. Focal mechanisms for these events will be obtained using regional and teleseismic data from permanent stations, and the hypocentral locations will be refined by modeling local/regional waveforms from the Tanzania Broadband Seismic Experiment.

OBJECTIVE

In this project, our purpose is to develop a catalog of reference events (ground truth) in the northeast African area of interest where reference event coverage is exceptionally poor due to the limited station coverage in the past.

Introduction

Earthquakes in northeastern Africa provide a principal source of ground truth for North Africa and the Middle East. The earthquakes of interest are associated with the northern and central portions of the East African Rift System (Figure 1). Since there are very few earthquakes within North Africa proper or within large parts of the Middle East that can be used to develop a set of ground truth, naturally occurring events in northeastern Africa take on an added importance for improving nuclear explosion monitoring capabilities in the region.

The development of ground truth for North Africa and the Middle East has in the past been limited not only by the lack of appreciable seismicity within North Africa and parts of the Middle East but also by a dearth of seismic stations throughout most of Africa. This situation is now changing. We operated regional seismic networks in Ethiopia and Kenya comprised of 27 and 11 broadband stations, respectively, between 2000 and 2002, and several years ago (1994-1995) we operated a similar network of 20 broadband seismic stations in Tanzania. The broadband waveforms recorded by these networks, together with waveforms from primary and auxiliary IMS stations in the region, provide a rich data set that can be used to accurately locate earthquakes and determine their origin times and source mechanisms.

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Here we present preliminary locations for several events with M>4 in East Africa constrained by P and S arrival times recorded by the regional broadband network in Tanzania. We begin by providing background information about the geology of the region and on the broadband seismic experiments. This is followed by a discussion of our event locations and uncertainties, and we conclude with a brief description of future work.

RESEARCH ACCOMPLISHED

Background Information

The locations of the broadband seismic experiments, together with the geology and topography of East Africa, are shown in Figure 1. The geology of the region comprises an Archean craton (the Tanzania Craton, Figure 1) surrounded by Proterozoic mobile belts. The rift faults of the Cenozoic East African rift system have developed mainly within the Proterozoic mobile belts, forming a rift system with two branches (Western rift and Eastern rift).

The broadband seismic experiment in Tanzania was conducted in 1994 and 1995 and consisted of 20 seismic stations deployed for a year in two skewed arrays, one oriented more or less east-west, and the other northeast-southwest. The experiment was designed so that structure beneath the Archean Tanzania Craton and the terminus of the Eastern Rift in northern Tanzania could be imaged with seismic data from local, regional and teleseismic earthquakes. Information about the station configuration, recording parameters and other details of the field deployment have been reported by Nyblade *et al*. (1996).

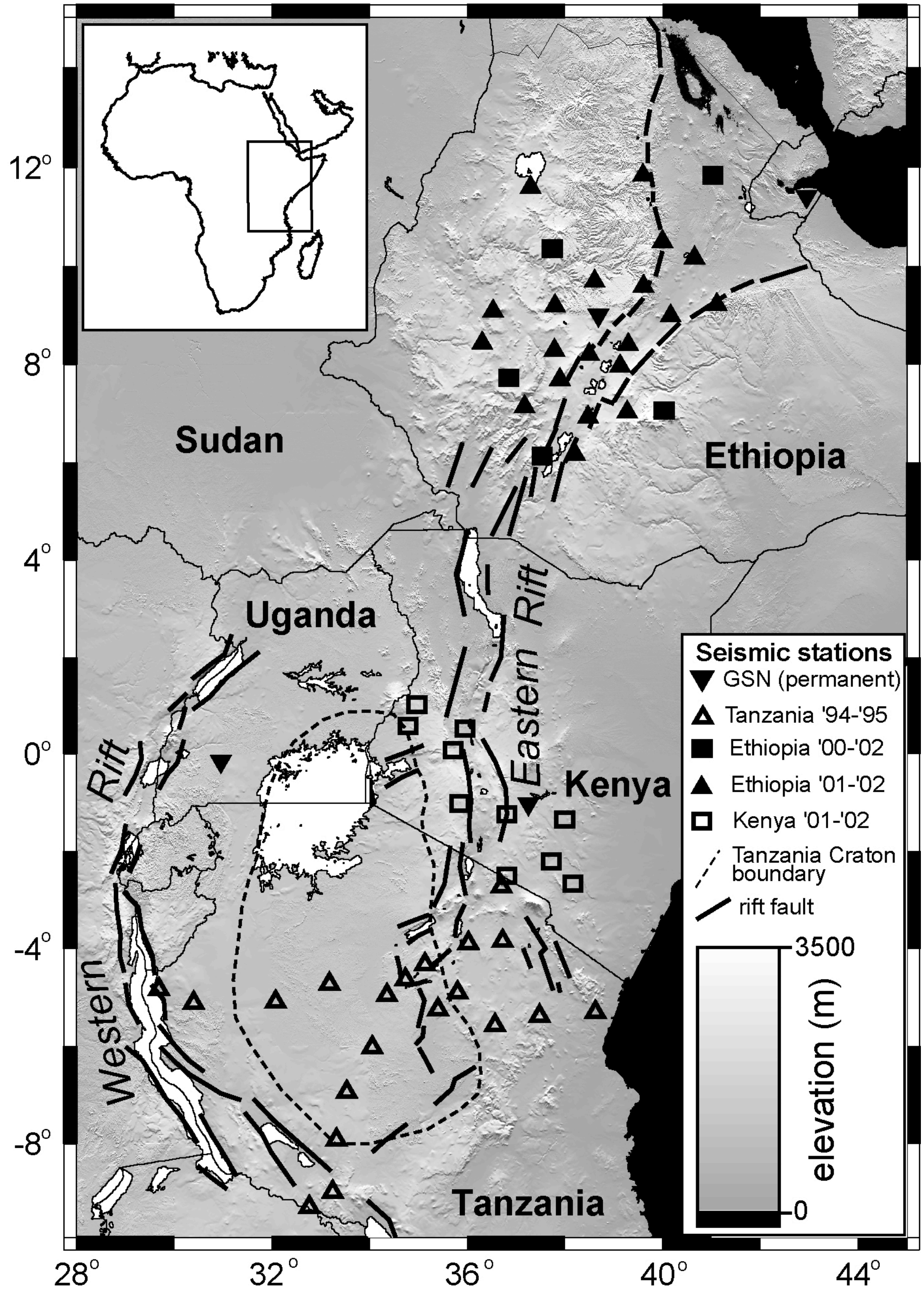

Figure 1. Topographic map of East Africa showing the Ethiopian and East African plateaus (regions with > 1000 m elevation), the outline of the Archean Tanzania craton, the major rift faults of the East African rift system, and the location of broadband seismic stations.

In the other broadband seismic experiments, seismic stations consisting of broadband sensors, 24-bit data loggers, 4-Gbyte hard disks, and Global Positioning System (GPS) clocks were deployed in regions of Ethiopia and Kenya safe for traveling (Figure 1). The stations were spaced 50 to 200 km apart and were located to optimize the recording of teleseismic body and surface waves that sample upper mantle structure beneath the Eastern Rift. For East Africa, the major source regions for teleseismic earthquakes are the Hindu Kush/Pamir region to the northeast and the Fiji/Tonga subduction zones to the east. Additional criteria used for site selection included access to bedrock, security, and year-round road conditions.

Installation of the Ethiopian stations was completed in two phases. During March 2000, five stations were installed around the periphery of the network, and then one year later (March 2001), an additional 20 stations were installed to make the network denser (Figure 1). All 25 stations were removed from the field in March 2002. Installation of the Kenyan stations took place during July and August 2001, and all 10 of the stations were removed in July 2002. Two data streams were recorded, a one sample/sec continuous stream and a twenty sample/sec continuous stream, yielding a data volume of 21 Mbytes per station per day. Data recovery for the Ethiopian stations was nearly 90%, and it was about 70% for the Kenyan stations.

Preliminary Event Locations

Preliminary event locations have been obtained for several events in East Africa with magnitudes ≥ 4 that were well recorded by the Tanzania Broadband Seismic Experiment. The preliminary locations were obtained using P and S arrival times, a regional velocity model for the crust and upper mantle constrained by a number of previous studies, and the event location code HYPOELLIPSE (Lahr, 1993). The P and S onset times were individually hand picked to within 0.1 seconds. A single velocity model representative of the entire area within the seismic network was used in the event location code and is shown in Table 1. Crust and uppermost mantle in East Africa has been studied in detail by many authors using refraction surveys, receiver functions, surface waves, regional waveforms and Pn tomography. From these studies, it is clear that crustal and uppermost mantle structure is fairly uniform in the Precambrian terrains away from the rift valleys proper (Last *et al*., 1997; Brazier *et al*., 2000; Nyblade, 2002; Langston *et al*., 2002; Fuchs *et al.* 1997 and references therein). Only minor differences in crustal thickness (2-5 km), mean crustal velocity (0.1-0.2 km/s), and uppermost mantle P velocities (0.1 – 0.2 km/s) are found between the various stations of the Tanzania network, and these differences introduce very small uncertainties in the event locations.

Table 1. Crust and uppermost mantle seismic structure for East Africa.

V1 (km/s)	V2 (km/s)	Poisson's Ratio	Moho Depth (km)	Mean crustal Vp (km/s)	Pn (km/s)
5.84	7.09	0.25	38	6.5	8.3

V1= uppermost crustal velocity; V2=lowermost crustal velocity

Table 2 summarizes the preliminary event origin times and locations, and the uncertainties associated with the locations. All of the events are well recorded on at least 11 stations over an azimuthal range of 130 or more degrees. A number of the events are within a few tens of kilometers of a station and none are more than a few hundred kilometers from a station. The magnitude estimates for these events come from using the maximum P wave amplitude within the first 5 seconds and the local magnitude scale for East Africa determined by Langston *et al*. (1998). Standard statistical measures at the 68% confidence interval in the error ellipse indicate that the hypocenters appear to be constrained to within a few kilometers. However, a detailed study of several of these events using regional waveform modeling (Langston *et al*., 2002) indicates that while the P and S arrival times do a fairly good job at constraining epicentral location, they do not provide tight constraints on source depth. Source depth for the events studied by Langston *et al*. (2002) are shown in Table 2. The source depth obtained from the P and S arrival times for these events differed from the source depths in Table 2 by 10 or more km.

For comparison, we also show in Table 2 the locations and origin times for several of the events taken from the International Seismic Centre (ISC) catalog. The comparison shows discrepancies in origin times of several seconds in most cases, and differences in event location of many tens of kilometers for some events. In addition, no catalog listings were found for two of the events.

CONCLUSIONS AND RECOMMENDATIONS

Future work will focus on obtaining accurate hypocenters for the regionally recorded events in Table 2 and many other events recorded on the Ethiopia and Kenya stations using a combination of proven modeling techniques. To improve upon the preliminary locations obtained from P and S arrival times, data from the closest stations will be used to determine incidence angles and ray parameters. By comparing them to theoretical values, source depth, epicentral distance, and back azimuth will be constrained. To refine the source depth estimate, depth phases recorded on nearby stations will be modeled assuming point dislocation sources. With source depths tightly constrained, the P and S arrival times can then be used to relocate epicenters. Finally, focal mechanisms will be determined using polarities and amplitudes of local and regional P and S phases in a grid-search technique, and the focal mechanisms will then be used with a wave number integration algorithm to compute full synthetic seismograms for several stations as a final check on the accuracy of the hypocenters.

In all of these steps it is crucial to have good velocity models for the crust and upper mantle. We will use analyses of receiver functions, surface waves and seismic refraction profiles to provide independent estimates of crustal and mantle velocities. In addition, we will make surface wave dispersion measurements of data from the three regional networks in the area. We will measure both Love and Rayleigh surface wave group velocities using a multiple narrow-band filter technique. Combined with thousands of other measurement made in the broader regional area (Pasyanos *et al*., 2001), we will conduct a high-resolution group velocity tomography of northeastern Africa. Using near-regional data will enable us to make more accurate short-period (5-15 seconds) measurements, which will allow us to constrain velocities in the uppermost crust. We will use the surface wave work, along with receiver functions and other data, to improve the velocity model of the crust and upper mantle, which will in turn improve the event locations.

To expand the catalog of events in northeastern Africa meeting the GT 10 specifications, we will take the events located using the approach described above and use them as calibration events to construct travel-time correction surfaces using the kriging method of Schultz *et al*., (1998, 1999) and Myers and Schultz (2000). The travel-time correction surfaces will then be used together with local and regional P arrivals to determine epicenters and origin times for numerous other events in the Ethiopia, Kenya and Tanzania data sets. Based on the expected proximity of many of these events to recording stations, we anticipate that there will be several tens of events whose epicenters will be determined to within 10 km.

The travel-time correction surfaces will be constructed following the approach outlined by Myers and Schultz (2000). For the regional networks, we will calculate travel-time residuals for the calibration events relative to a regional velocity model. The travel-time residuals will be assigned to the respective calibration epicenter, forming a set of spatially varying travel-time correction points. This set of points will then be declustered to reduce the dimensions of the observations, and this refined set of calibration points will be used with Bayesian kriging to form continuous travel-time surfaces that will provide source-specific corrections for each station in the regional networks. In locating epicenters, a standard location algorithm will be used with the kriging corrections applied. A conservative uncertainty estimate for the kriging correction will be used to characterize the travel-time-predication error, according to the procedure followed by Myers and Schultz (2000). This conservative estimate will be developed using rigorous statistical modeling with available seismic data. Cross-validations will be provided to ensure that the estimates are accurate. In general, these statistics will be used as input to generate chi-squared for robustly determining the final reference event error ellipses.

Table 2. Preliminary locations for earthquakes in East Africa with M > 4 from July 1994 – June 1995 recorded by the Tanzania Broadband Seismic Experiment.

Event: source	Yr:mo:day:hr:min:sec	Lat.	Lon.	D	M	N	Gap	RMS	Smaj	Az	Smin	Sez
1:This paper	94:07:20:11:32:04.30	-4.080	35.440	42	4.5	19	141	0.44	0.25	-106	0.45	1.7
1:ISC	94:07:20:11:31:58.49	-4.171	35.185	0	3.8			1.26	10.4	90	6.6	
2: This paper	94:08:18:00:45:48.80	-7.440	31.770	25*	5.9	17	167	1.77	0.35	-34	0.48	2*
2: ISC	94:08:18:00:45:52.70	-7.650	31.830	25	5.9			0.69	2.20	90	2.20	
3: This paper	94:09:05:04:08:56.04	-7.508	31.700	?	4.1	15	174	0.43	0.41	-59	0.70	?
3: ISC	94:09:05:04:08:50.41	-7.738	30.882	4	4.6			1.38	10.9	90	6.3	
4: This paper	94:09:30:01:36:53.14	-5.920	29.890	26	4.5	16	229	1.13	0.55	-40	1.18	1.4
4: ISC	94:09:30:01:36:47.62	-8.426	37.261	0	4.4			1.78	15.6	90	8.6	
5: This paper	94:11:12:12:18:00.00	-6.950	29.920	30*	5.3	16	221	0.55	0.42	-24	0.89	2*
5: ISC	94:11:12:12:18:01.33	-6.777	29.821	22	4.6			1.05	6.3	90	4.5	
6: This paper	94:11:12:20:16:59.37	-6.617	30.016	?	4.7	17	223	0.88	0.45	-33	0.96	?
6: ISC	94:11:12:20:16:49.66	-6.834	29.946	0	4.6			1.15	8.4	90	5.5	
7: This paper	94:11:16:01:08:11.20	-9.070	33.330	8*	4.5	17	193	0.80	0.48	-129	0.66	2*
7: ISC	94:11:16:01:08:09.07	-9.179	33.273	10	5.0			1.64	7.8	90	6.8	
8: This paper	94:11:27:04:20:51.65	-3.568	35.827	30	4.0	15	213	0.51	0.36	-93	0.95	0.7
8: ISC	94:11:27:04:20:44.27	-3.954	35.722	10	4.0			0.12	22.4	90	10.1	
9: This paper	94:12:25:04:25:27.44	-5.113	29.752	21	4.2	11	301	0.59	0.81	19	6.42	1.9
9: ISC	No listing											
10: This paper	95:01:29:00:23:35.02	-5.419	35.909	13	4.1	11	128	0.37	0.34	-107	0.51	1.0
10: ISC	No listing											

D = depth in km. * = depth was determined from regional depth phases (Langston *et al*., 2002). Otherwise depths were determined from only P and S arrival times.

M = magnitude. Magnitudes in this study are based on the ML scale from Langston *et al*. (1998). ISC magnitudes are a mixture of different types.

N = number of stations used in the event location.

Gap = azimuth range in stations.

RMS = Rms error in arrival times.

Smaj, Smin, Sez, Az = dimensions (in km) and orientation of the error ellipse. For this study, the numbers in the table are for a 68% confidence level. * on Sez numbers indicates that the depth uncertainty was obtained from modeling regional depth phases (Langston et al., 2002).

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