GROUND TRUTH EVENTS, MAGNITUDE SCALE, VELOCITY MODELS AND TRAVEL TIME CORRECTION SURFACES FOR NORTHEASTERN AFRICA

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ABSTRACT

Determining accurate seismic locations with representative uncertainty estimates is of fundamental importance to ground-based nuclear explosion monitoring. This project has developed a catalog of reference events (ground truth) in the northeast African area of interest where reference event coverage is exceptionally poor. The results of this project 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 collection of ground truth events for northeastern Africa has been achieved using broadband seismic data from regional PASSCAL networks in Ethiopia, Kenya and Tanzania, as well as broadband data from primary and auxiliary International Monitoring System stations in the region. Accurate event locations for twenty-two M>3.5 events are reported. For events in Tanzania, focal mechanisms have been obtained by modeling P and SH polarities and amplitude ratios in a grid search method. Epicenters have been constrained by using P and S arrival times, and focal depths have been constrained by waveform modeling of regional and local depth phases. Most of the earthquakes occur on either the western or eastern branch of the East African Rift, and the mechanisms obtained are all normal or strike-slip. For events in Ethiopia, epicentral locations have been obtained using only P arrival times. Eleven events from Ethiopia and one from Tanzania meet either the GT5 local and/or the GT20 regional criteria of Bondar et al. (2004).

Within this project, several other efforts have been undertaken to improve monitoring capabilities in northeastern Africa. A Bayesian kriging method has been used with the well located events to construct regional travel-time correction surfaces. Group velocity measurements from many thousand station-event pairs for 10-60 second Rayleigh and Love waves have been measured, and these measurements have been inverted to produce group velocity maps of northeastern Africa, and new models of crust and uppermost mantle structure in southern Ethiopia and northern Kenya. A new local magnitude scale for Ethiopia has also been developed.

OBJECTIVE

The objectives of this project are to provide 1) a reference catalog of accurately located earthquakes for northeastern Africa, 2) a local magnitude scale for Ethiopia, 3) improved velocity models of the crust and upper mantle for northeastern Africa, and 4) new travel time correction surfaces.

INTRODUCTION

Determining accurate seismic locations with representative uncertainty estimates is of fundamental importance to ground-based nuclear explosion monitoring. In this project, we have developed a catalog of reference events (ground- truth [GT]) for northeastern Africa where reference event coverage is exceptionally poor due to the limited station coverage by historic networks. 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.

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 monitoring capabilities in the region.

The development of GT for North Africa and the Middle East has in the past been limited not only by the lack of appreciable seismicity 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 origin times and source mechanisms.

Accurate event locations for twenty-two M>3.5 events are reported. For events in Tanzania, focal mechanisms have been obtained by modeling P and SH polarities and amplitude ratios in a grid search method. Epicenters have been constrained by using P and S arrival times, and focal depths have been constrained by waveform modeling of regional and local depth phases. Most of the earthquakes occur on either the western or eastern branch of the East African Rift, and the mechanisms obtained are all normal or strike-slip. For events in Ethiopia, epicentral locations have been obtained using only P arrival times. Eleven events from Ethiopia and one from Tanzania meet either the GT5 local and/or the GT20 regional criteria of Bondar et al. (2004).

Within this project, several other efforts have been undertaken to improve monitoring capabilities in northeastern Africa. A Bayesian kriging method has been used with the well located events to construct regional travel-time correction surfaces. Group velocity measurements from many thousand station-event pairs for 10-60 second Rayleigh and Love waves have been measured, and these measurements have been inverted to produce group velocity maps of northeastern Africa, and new models of crust and uppermost mantle structure in southern Ethiopia and northern Kenya. A new local magnitude scale for Ethiopia has also been developed.

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 is comprised of 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 that begins with the Main Ethiopian Rift intersecting the Red Sea and the Gulf of Aden at the Afar triple junction continuing southwest through Kenya and splitting into two branches (Western rift and Eastern rift) around the Tanzanian Craton.

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 has been reported by Nyblade et al. (1996).

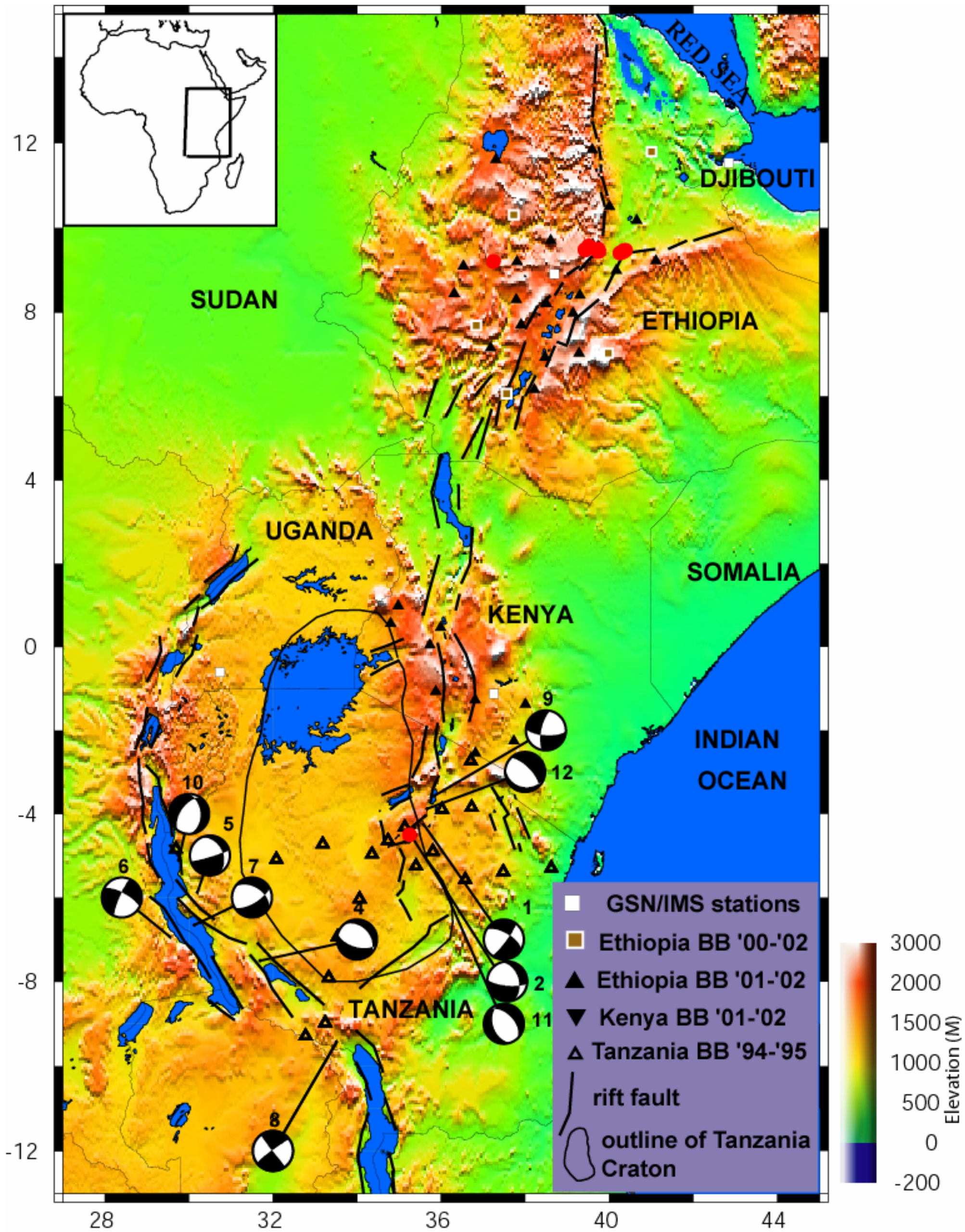

Figure 1. Topographic map of East Africa showing the Ethiopian and East African plateaus (regions with > 1000 m elevation), the outline of the Archean Tanzania craton, the major rift faults of the East African rift system, focal mechanisms and locations for our GT events (red circles), and the location 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 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 densify the network (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 1 sample/sec continuous stream and a 20 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.

EVENT LOCATIONS

Event locations have been obtained for several events in Tanzania with magnitudes $\geq$ 3.7 and in Ethiopia with magnitudes > 2.4 that were well recorded by the Tanzania and Ethiopia regional networks. The locations were obtained using P and S arrival times for events in Tanzania, P arrival times for events in Ethiopia, a regional velocity model for the crust and upper mantle constrained by previous studies, and the event location code HYPOELLIPSE (Lahr, 1993). The P and S onset times were individually handpicked to within 0.1 seconds. The velocity model in Table 1 was used in event location in Tanzania. 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 in Tanzania 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. For locating events in Ethiopia, we used station dependent velocity models determined by Dugda et al. (2005).

TABLE 1. Crust and uppermost mantle seismic structure for Tanzania and Ethiopia, East Africa.

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

V1= uppermost crustal velocity; V2=lowermost crustal velocity

Table 2 summarizes the event origin times and locations, and the uncertainties from Hypoellipse associated with the locations. All of the events are well recorded on at least 11 stations. 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 the Tanzania events comes from using the maximum surface wave amplitude and the local magnitude scale for East Africa determined by Langston et al. (1998). Magnitudes for events in Ethiopia given in Table 2 come from a new local magnitude scale given below.

Focal mechanisms for the Tanzania events have been determined using polarities and amplitude ratios of local and regional P and S phases in a grid-search technique (Snoke et al., 1984) and are plotted in Figure 1 and listed in Table 3. The focal mechanisms were then used with a wavenumber integration algorithm (Kennett, 1983) to compute full synthetic seismograms for several stations at several depths. The synthetics were compared against the data and regional depth phases such as pPn, sPn and PmP were identified to constrain the source depths. An example is shown in Figure 2 and a complete description in Brazier et al. (2005). In addition, eleven events from Ethiopia and one from Tanzania meet either the GT5 local and/or the GT20 regional criteria set by Bondar et al., (2004) and are listed in Table 4.

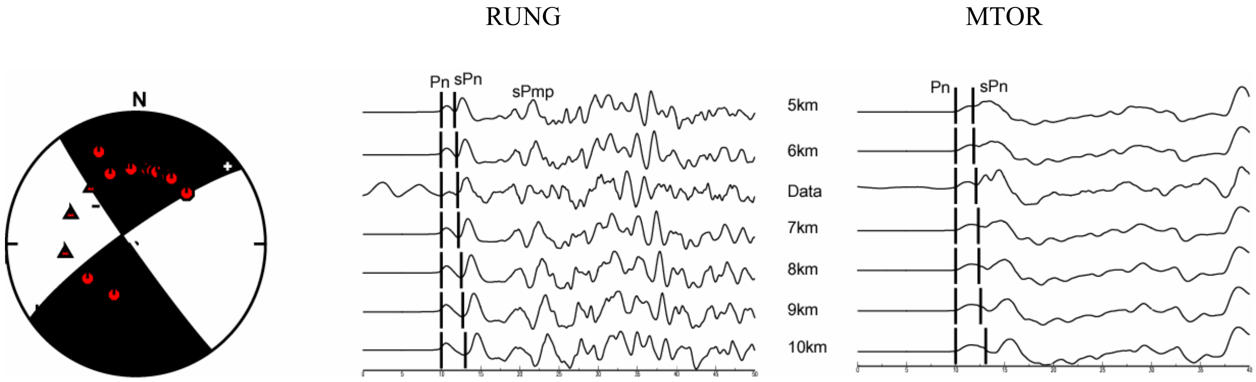

Figure 2 Vertical displacement waveforms and focal mechanisms from the November 16 1994, Mbeya event (No. 8: in Table 2) recorded at RUNG ($\Delta = 248$ km) and MTOR ($\Delta = 480$ km) and synthetics for source depths between 5-10 km. Traces are aligned on Pn and depth phases sPn and sPmp are noted. Circles are compressional first motions; triangles are dilatational first motions.

TABLE 2. Locations for earthquakes in East Africa, from July 1994 to June 1995, recorded by the Tanzania Broadband Seismic Experiment and from April 2000 to March 2002 by the Ethiopian Broadband Experiment.

Ev	yr:mo:day:hr:min:sec	Lat.	Lon.	Dep	M	N	Gap	RMS	Smaj	Az	Smin	Sez
1	94:07:20:11:32:04.09	-4.225	35.585	29	4.5	19	133	1.52	0.25	-106	0.40	0.47
2	94:08:17:03:23:32.68	-4.448	35.585	13	3.7	20	71	4.05	0.22	-105	0.31	0.52
4	94:09:05:04:08:54.83	-7.502	31.700	15	4.1	18	174	0.54	0.38	-50	0.55	2
5	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
6	94:11:12:12:17:57.73	-6.939	29.552	18	5.3	23	94	2.13	0.31	-40	0.36	2
7	94:11:12:20:16:58.19	-6.652	30.135	8	4.7	17	211	1.29	0.39	-26	0.73	2
8	94:11:16:01:08:05.78	-9.424	33.513	7	4.5	20	150	3.6	0.29	-52	0.54	0.97
9	94:11:27:04:20:53.71	-4.084	35.828	11	4.0	15	146	2.28	0.29	-112	0.48	0.7
10	94:12:25:04:25:35.97	-5.173	30.580	29	4.2	11	150	1.48	0.67	22	4.98	2
11	95:01:29:00:23:33.29	-5.033	35.923	9	4.1	11	111	3.51	0.31	-111	0.53	1.04
12	95:02:12:16:37:33.85	-3.879	35.670	34	4.5	13	215	0.56	0.36	-107	0.96	2
13	01:07:13:22:34:15.21	9.426	40.270		3.0	20	90	2.17	0.23	-56	0.31	0.55
14	01:06:26:22:22:07.36	9.394	40.391		3.3	17	99	2.30	0.26	-78	0.40	0.69
15	01:06:23:20:00:24.18	9.413	40.254		3.5	19	89	2.93	0.23	-67	0.35	0.66
16	01:06:26:22:32:19.97	9.434	40.339		3.5	18	89	2.20	0.25	-66	0.36	0.71
17	01:05:23:01:16:11.41	9.465	39.410		3.4	24	61	2.13	0.19	-47	0.28	0.5
18	01:11:11:21:05:22.89	9.511	39.691			10	71	0.58	0.32	-71	0.36	0.66
19	01:11:11:22:32:42.83	9.442	39.722			22	43	1.83	0.21	-67	0.25	0.49
20	01:11:11:22:38:04.17	9.487	39.727		3.7	22	45	1.47	0.21	-60	0.25	0.82
21	01:11:27:21:35:36.86	9.477	39.705		2.4	14	68	1.63	0.27	-51	0.30	0.64
22	01:12:13:02:14:40.67	9.497	39.705		3.0	16	63	1.58	0.24	-63	0.29	0.58
23	01:05:12:02:06:42.39	9.507	39.710		2.7	15	61	1.06	0.27	6	0.28	0.60

Dep = depth in km.
M = magnitude. Magnitudes for Tanzanian events are based on the ML scale from Langston et al. (1998), and the new scale presented in this text for events in Ethiopia
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 kms) and orientation of the error ellipse. For this study, the numbers in the table are for a 68% confidence level.

Table 3. Focal mechanisms for events in Table 2

Ev.	Strike (deg)	Dip (deg)	Rake (deg)
1	301	64	-11
2	335	35	-10
4	318	36	-63
5	335	36	-10
6	204	80	-20
7	303	46	-35
8	143	88	-5
9	93	69	-22
10	215	55	-65
11	162	43	-71
12	316	68	-77

Table 4 GT level for events in Table 2

Event	Gap	Secondary Gap	No. stations < 2.5 deg.	No. stations Between 2.5 and 10 deg.	No. stations < 30km	GT level
2	71	133	12	8	1	GT5
13	90	103	9	11	0	GT20
14	99	105	5	12	0	GT20
15	89	100	7	12	0	GT20
16	89	101	5	13	0	GT20
17	61	85	14	10	1	GT5/20
18	71	120	10	0	1	GT5
19	43	80	12	10	0	GT20
20	45	86	12	10	1	GT5/20
21	68	104	11	4	1	GT5
22	63	100	11	5	1	GT5
23	61	101	12	3	1	GT5

Secondary Gap = azimuth range in stations with one station omitted.

LOCAL MAGNITUDE SCALE

We have developed a new magnitude scale following Richter's (1958) method, based on the seismograms recorded by Wood-Anderson instruments with period T_0 = 0.8 sec, magnification = 2800 and damping = 0.8. The local magnitude M_L is defined as:

$$M_L = \log A - \log A_0 + S \qquad (1)$$

where A is the trace maximum amplitude observed on the horizontal components of the seismogram; A_0 is an empirically determined distance curve with assumption that when the maximum amplitude of 1 mm is observed at a distance of 100 km, M_L = 3.0; S is an empirically determined station correction. Following Hutton and Boore (1987), the distance-correction curve can be written as:

$$\log A_{ij} = -n \log(r_{ij}/100) - K(r_{ij} - 100) - 3.0 \qquad (2)$$

Where n and K are parameters related to the geometrical spreading and attenuation; A_{ij} is the horizontal maximum amplitude of the i^{th} event observed at the j^{th} station; r_{ij} is the distance from the epicenter of the i^{th} event to the j^{th} station. Combining equations (1) and (2):

$$-n \log(r_{ij}/100) - K(r_{ij} - 100) + M_{Li} - S_{jk} = \log A_{ijk} + 3.0, \qquad (3)$$

where M_{Li} is the local magnitude of the i^{th} event and S_{jk} is the correction for the j^{th} station on the k^{th} component. Based on equation (3), the parameters *n*, *K*, local magnitude M_L and station correction S can be solved using the generalized inversion method (Aki and Richards, 1980), as several investigators have done before (Hutton and Boore, 1987; Langston et al., 1998). We inverted for 58 station factors and 2 model parameters, n and K. All the stations are in a similar region, and therefore we assume the station factors average to zero. This is added as a constraint to the system of equations.

As opposed to Langston et al. (1998), we performed the inversion in a single step calculating all 60 parameters at once, avoiding the convergence issues of an iterative method. The inversion included 446 events and nearly 6000 amplitudes, yielding values $n = 0.60812$ and $K = 0.00036301$. The magnitude scale for Ethiopia in comparison to the Tanzania local magnitude scale (Langston et al., 1998) has high attenuation. The Tanzania scale needed a equivalent motion stipulation at 17 km as opposed to 100 km to avoid the attenuation effect. The ML residuals are normally distributed with no outliers. The residuals are also linearly distributed when plotted against distance. Details of the inversion and local magnitude scale can be found in Brazier et al. (manuscript in prep.).

VELOCITY MODELS

To improve regional velocity models for the study area, we have made surface wave dispersion measurements for both Love and Rayleigh 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 have performed a high resolution group velocity tomography of northeastern Africa. Surface wave tomography results can be seen in Figure 3 for 10 to 60 second period Rayleigh waves. These maps have been inverted for crustal and upper mantle structure using a grid search approach (Benoit, 2005). Results are shown in Figure 4.

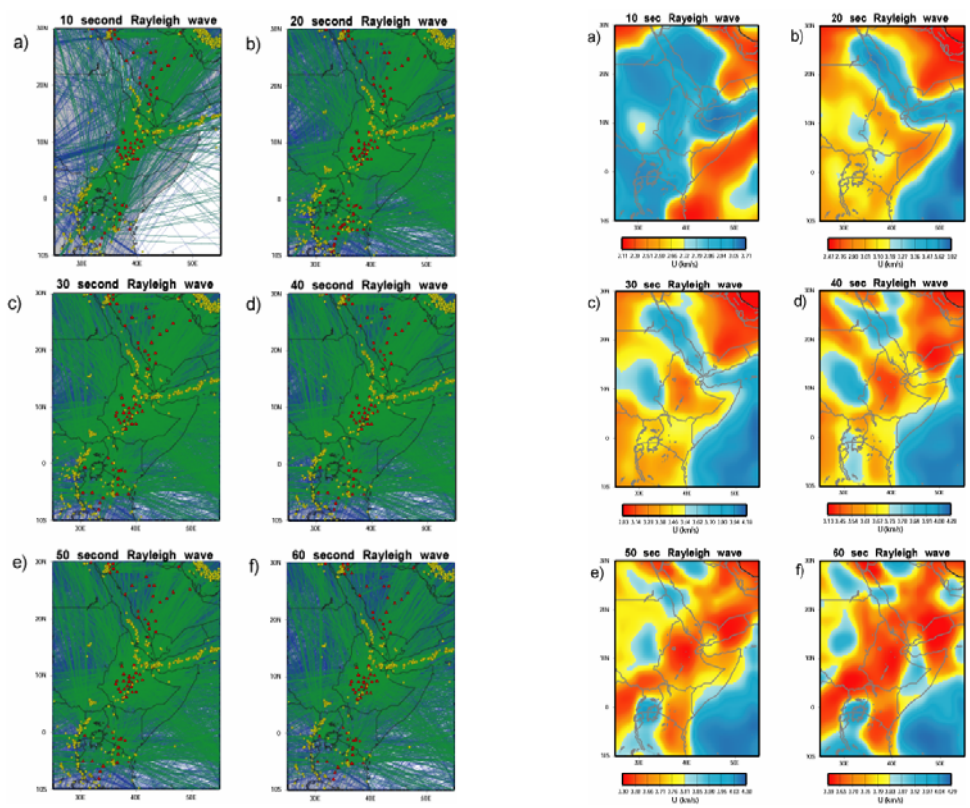

Figure 3. Path locations and results of the tomography for 10 to 60 second Rayleigh waves

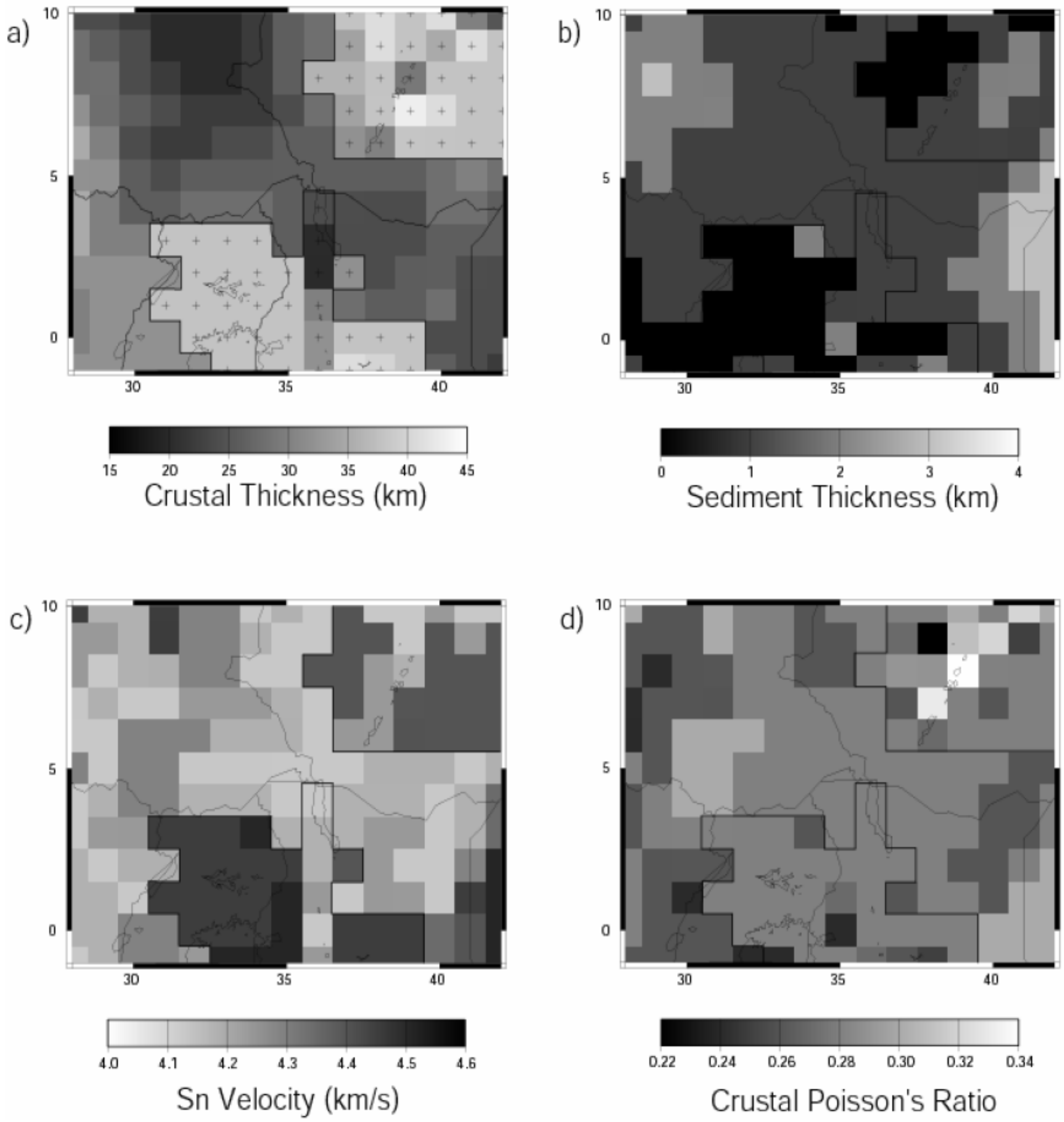

Figure 4. Crustal structure constructed from the surface wave tomography

TRAVEL-TIME CORRECTION SURFACES

To expand the catalog of events in northeastern Africa, we have taken the GT events from Table 2 and used them along with teleseimic GT15-25 events (Engdahl et. al., 1998) as calibration events to construct travel-time correction surfaces using the kriging method of Schultz et al. (1998, 1999) and Myers and Schultz (2000). P-wave results for station BGCA can be seen in Figure 5. P and S correction surfaces have been developed for stations DBIC, BOSA, LBTB, and TAM.

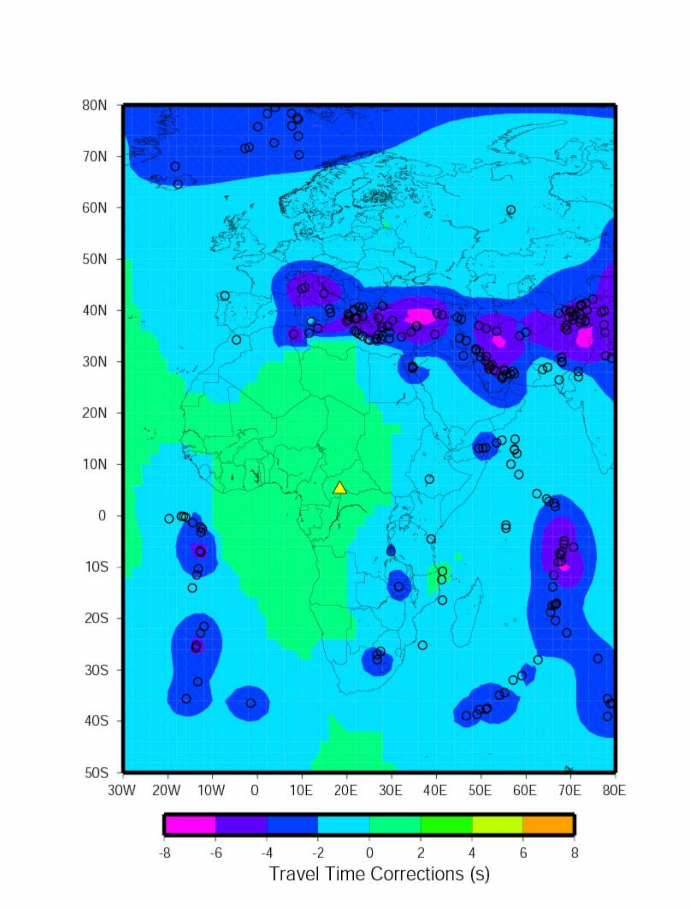

Figure 5 P wave traveltime correction surface for BGCA in the Central African Republic.

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