Scientific Report to the NERC Geophysical Equipment Facility for GEF loan 913

Rifting in the Horn of Africa: The Eritrea Seismic Project (June 2011 – October 2012)

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Abstract
SEIS-UK provided a loan of 6 broadband seismic systems (5 x CMGESP, 1 x CMG3T, 1 x CMG40T) for a period of 16 months, for deployment in a network that extended ~500 km across Eritrea from Asmara in the highlands to Assab on the edge of the Danakil in southern Eritrea. The SEIS-UK deployment was coeval with a BHP-Billiton funded array of 13 seismometers in the Danakil depression, Ethiopia (GEF loan 885) and the YOCMAL array of 50 seismometers in Yemen (GEF loan 873). The Eritrean systems recorded continuously at 100/50Hz with relatively minor data losses due to equipment problems. All data are archived on the SEISUK system and will be sent to IRIS (Incorporated Research Institutions for Seismology) and made publicly available in October 2015. The use of the Eritrean seismic data, together with Ethiopian and Yemen data has allowed us to produce high-resolution images of the crust, upper and mid-mantle (to depths of 900 km) beneath the Horn of Africa. Body-wave and surface wave tomography show focussed, melt related, anomalies in the top 100km of the lithosphere with multiple upwellings transcending the transition zone with their origin likely in the lower mantle. Receiver function estimates of transition zone structure show evidence for a stable melt layer atop the 410 km mantle discontinuity, suggesting the upwellings in the transition zone have a significant hydrous component. Receiver functions have also provided the first estimates of crustal structure in Eritrea, providing further understanding on the breakup history of Afar. Fortuitously, the seismometers were deployed just days after the eruption of Nabro Volcano in Eritrea, thus they (together with stations in Ethiopia) have provided important data to characterise the nature of this, the first ever recorded eruption of the volcano. Data from these stations (together with data from other regional networks) continues to be used to measure seismic anisotropy from splitting of SKS-waves and local earthquake S-wave data, estimate locations of local seismicity and to produce Pn tomographic images of the uppermost mantle. All these results have been presented at international conferences and have been and are currently being written up for leading international journals.

Background
Over the last 2 decades much seismic research has been conducted in Ethiopia to understand the late stages of continental rifting (Nyblade and Langston, 2002, Maguire et al., 2003, Ebinger et al., 2010, Belachew et al., 2010, Hammond et al., 2011) (Figure 1). These studies have produced unprecedented images of crust and mantle structure beneath the rift (Mackenzie et al., 2005, Benoit et al., 2006, Bastow et al., 2008, Hammond et al., 2011, Guidarelli et al., 2011, Stork et al., 2013, Hammond et al., 2013) furthering our understanding of rifting processes. Additionally, UK and French projects have been conducted in Djibouti and Yemen with the aim of further understanding the rifting process in the Horn of Africa. However, despite Eritrea hosting the northernmost extent of on-land Red Sea rift, and containing the majority of the Danakil microplate (a suspected isolated microcontinent between the Nubian and Arabian plates), little work has been conducted in the country. With this in mind a small project was designed to deploy 6 seismometers across Eritrea. The main aim of this array was to perform seismic tomography on all available data to produce high-resolution images in to the lower mantle (Hammond et al., 2013). The array also offers the chance to estimate crustal structure beneath this part of the Horn of Africa, elucidating the nature of the Red Sea rift and Danakil microplates, understand flow and melt storage from anisotropy and better locate seismicity in the region.

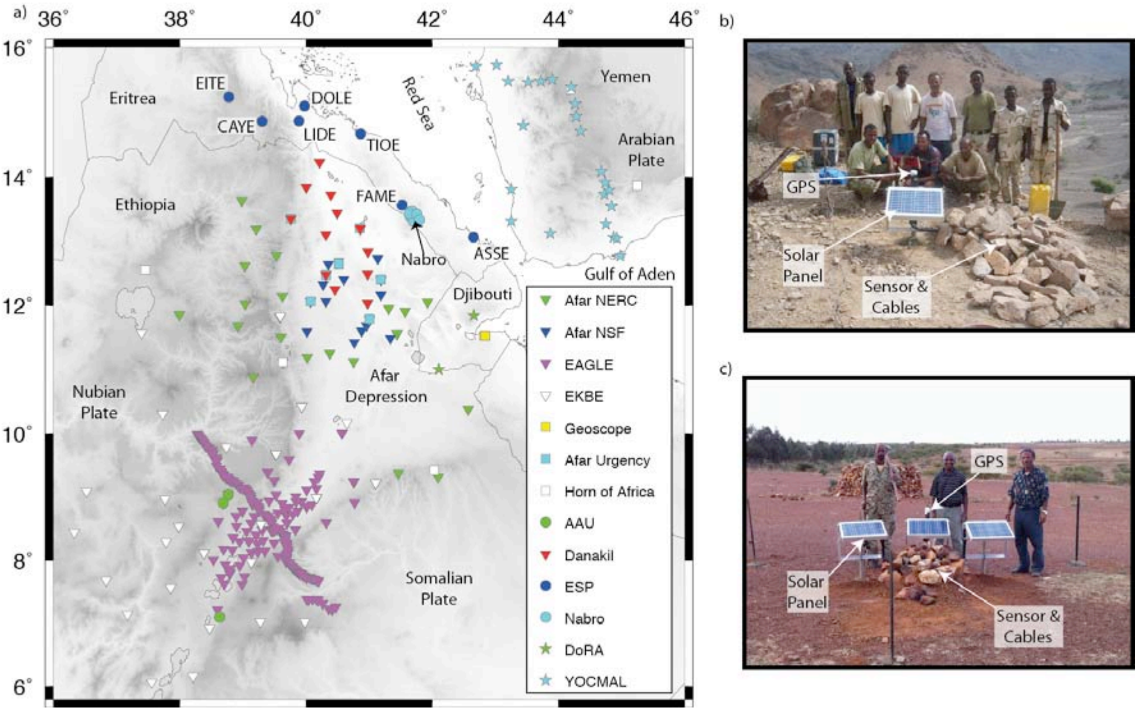

Figure 1. a) Distribution of stations throughout the Horn of Africa. Dark blue circles show stations deployed for the Eritrea Seismic Project. b) Deployment set up for the ESP at FAME. c) Deployment set up for the 3T station at EITE.

Survey Procedure

5 ESP and 1 3T seismometers were deployed in a linear profile with two stations in the highlands (EITE – Asmara, CAYE – Adi Keyih) 2 stations in the northern Red Sea region (DOLE – Berdole, TIOE – Tio) and 2 in the Southern Red Sea region (FAME – Afambo, ASSE – Assab) (Figure 1, Table 1). One CMG40T that was sent to Eritrea to replace a damaged sensor on the Nabro array (GEF loan 953) was deployed as part of the regional array. This was due to customs delays and logistical issues meaning it was not possible to visit Nabro to replace the sensor during the experiment window. To make use of the station it was deployed on Alid Volcano (station LIDE) in the northern Red Sea region (Figure 1).

Help and collaboration from the Eritrea Institute of Technology (EIT) (Prof. Ghebrebrhan Ogubazghi and Berhe Goitom), the Department of Mines and Energy (Alem Kibreab) and the Southern Red Sea regional administration was essential for the success of the project. Prof. Ogubazghi and Berhe Goitom performed a reconnaissance trip identifying suitable locations for our seismic sites. Our original plan was to deploy close to telecommunication towers as these offered good security and had been used previously by our EIT colleagues. However, local security concerns meant that these were not suitable and nearby sites in government offices and military camps were chosen. All stations were located in fenced compounds, or close to permanently occupied guard houses for security. The stations were deployed in June by Berhe Goitom (BG) and Ghebrebrhan Ogubazghi (GO), serviced in October 2011 by BG and James Hammond (JH) and May 2012 by BG and decommissioned in October 2012 by JH. Other members involved were Mebratu Fisseha, Michael Eyob (EIT) Goitom Kibrom, Ermias Yohannes (Ministry of Mines and Energy), and Clive Oppenheimer (Cambridge University). See Table 1 for station details. All stations recorded with a sampling rate of 50 Hz except LIDE, which recorded at 100Hz (Table 1).

A hole ~1m deep, ~0.7m in diameter, was dug at the site to house the seismometer. Where bedrock was encountered (Adi Caye) a small concrete slab was cemented to the bedrock, in other locations a sand layer was placed at the base of the hole with a level slab on top of the sand. The seismometer was then placed in a plastic bag on top of the slab, levelled and aligned with magnetic north, and the firewire and sensor cable attached. The hole was then back filled to bury the sensor. All stations were protected from the heat using reflective sheets.

A second hole close to the seismometer hole was dug, and a plastic bin placed inside. This was of a depth so that the bin was ~20cm above the surface. The battery (40 Ahr), break out box, and in the case of the CMG3T, the EAM data logger were placed in this box with all cables attached. Cables for the sensor and firewire led from this box to the seismometer hole. Cables for the GPS and solar panels led out of the box and connected with the solar panels and GPS antenna located nearby. All cables out of the box were fed through flexible plastic conduit and secured to posts or buried. The battery/cable box was then covered with insulation and plastic, and secured with tape. Due to the larger power requirements for the CMG3T and EAM data logger, 3 solar panels were deployed at this station (EITE) compared with 1 solar panel at the ESP seismic stations (Figure 2).

In general the stations worked well. A regulator problem at Berdolli (DOLE) meant that power was lost 11 days after deployment. This was replaced resulting in 87 days of lost data. Disk storage issues at EITE resulted in 41 lost days. An unknown power issue occurred at Assab (ASSE) resulting in 110 days lost data. In total data recovery was ~92%.

Station Code	Location	Sensor	Sensor ID	Latitude (°)	Longitude (°)	Elevation (m)	Start Date	End Date	Sample rate (Hz)
ASSE	Assab	ESP	T34564	13.0628	42.6545	19	22/06/2011	11/10/2012	50
CAYE	Adi Caieh	ESP	T34670	14.862	39.3051	2435	15/06/2011	14/10/2012	50
DOLE	Berdolli	ESP	T34569	15.0968	39.9806	88	20/06/2011	12/10/2012	50
EITE	Eritrea Institute of Technology (Mai Nefhi)	3T	T3A13	15.2359	38.7779	2171	17/06/2011	15/10/2012	50
FAME	Afambo	ESP	T34660	13.5684	41.5196	622	22/06/2011	06/10/2012	50
LIDE	Alid Volcano	40T	T4A96	14.8685	39.8864	317	10/07/2012	13/10/2012	100
TIOE	Tio	ESP	T35468	14.6651	40.8666	43	21/06/2011	12/10/2012	50

Table 1: ESP seismic network: Station details.

Data Quality

Data quality is excellent, largely due to the lack of cultural noise at most stations (Figure 3). Even the stations close to infrastructure (e.g., EITE, which is deployed at the Eritrea Institute of Technology) have noise levels at the low end of the lower end of the noise models of Peterson, 1993.

Processing

Data were processed and archived using the standard SEISUK procedures. Relative travel-time tomography was performed using the Vandecar et al., 1995 technique (see Hammond et al., 2013 for details related to these data). Surface wave inversions used standard array methods to invert for 1-D phase velocity dispersion and 2-D phase velocity maps (Yang and Forsyth, 2006). Receiver functions were estimated the iterative time domain approach (Ligorria and Ammon, 1999). Earthquakes have been located using standard techniques (e.g., HYPO2000)

Interpretation and preliminary findings

Uppermost mantle structure (< 200 km)

The Eritrean data were combined with other datasets from the region to invert for upper mantle structure. P- and S-wave models were produced using relative travel-time tomography (using the method of Vandecar et al., 1995) (Hammond et al., 2013) and Rayleigh wave tomography (using the method of Yang and Forsyth, 2006) (Gallacher et al., in prep). Both show evidence for strong low velocity anomalies in the upper mantle. The strong low velocities show the presence of melt related to decompression melting from passive upwelling.

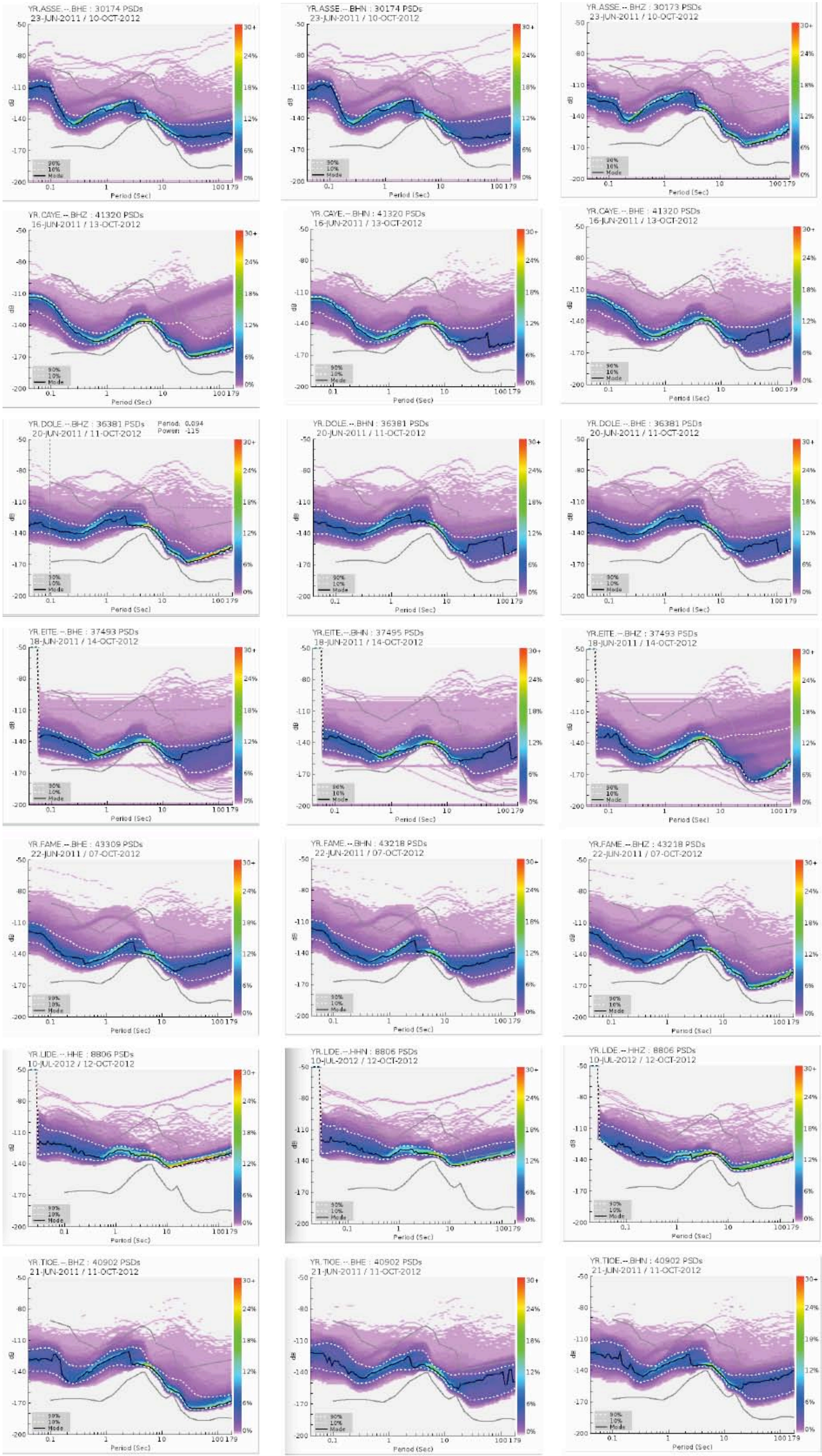

Figure 3: Power spectral density plots for all components for all seismic stations used in the project. The black lines show the high and low noise model of Peterson, 1993

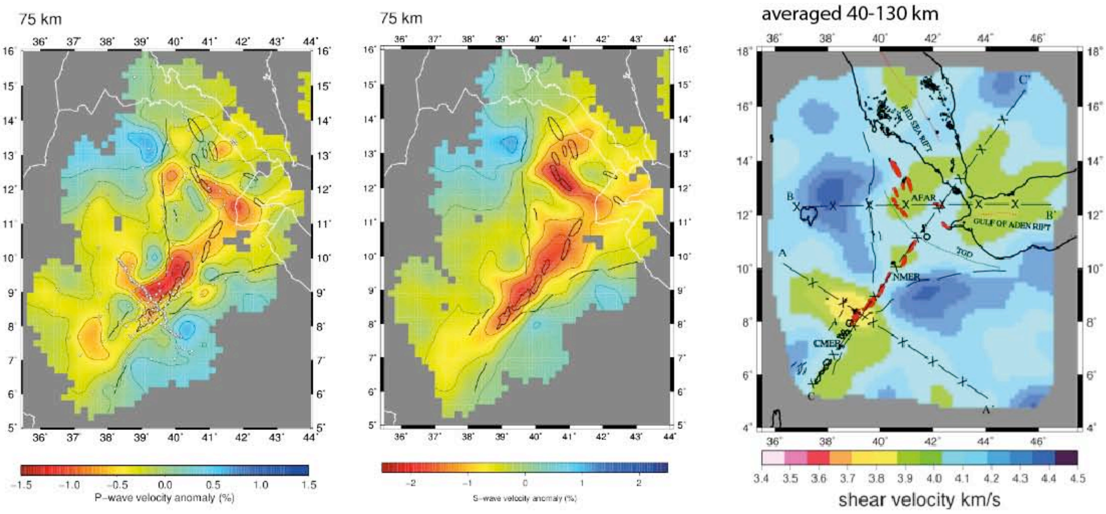

Figure 4: a) P-wave velocity structure at a depth of 75 km, b) S-wave velocity structure at a depth of 75 km, c) averaged S-wave velocity structure in the uppermost mantle. a) and b) are estimated using relative travel-time tomography (Hammond et al., 2013), c) is estimated using surface wave inversion (Gallacher et al., in prep).

Transition Zone structure

Receiver functions are estimated from the Eritrean data and combined with other regional datasets to determine the nature of the transition zone structure. Changes in temperature or composition can lead to topography on the 410km (410) and 660km (660) discontinuity (Helffrich, 2000). Results show that little topography exists, suggesting minimal thermal anomaly is present (<100°C) (Thompson et al., submitted) (Figure 4). However, a clear low velocity layer is observed in the receiver function data above the 410. This coincides with low seismic velocities and the presence of a sharp 520 km discontinuity directly below the feature, suggesting that a hydrous upwelling is causing melt to form above the transition zone. The results show that mantle plumes may be more complex than previously thought, and that in some regions are likely driven by differences in composition rather than temperature alone (Thompson et al., submitted).

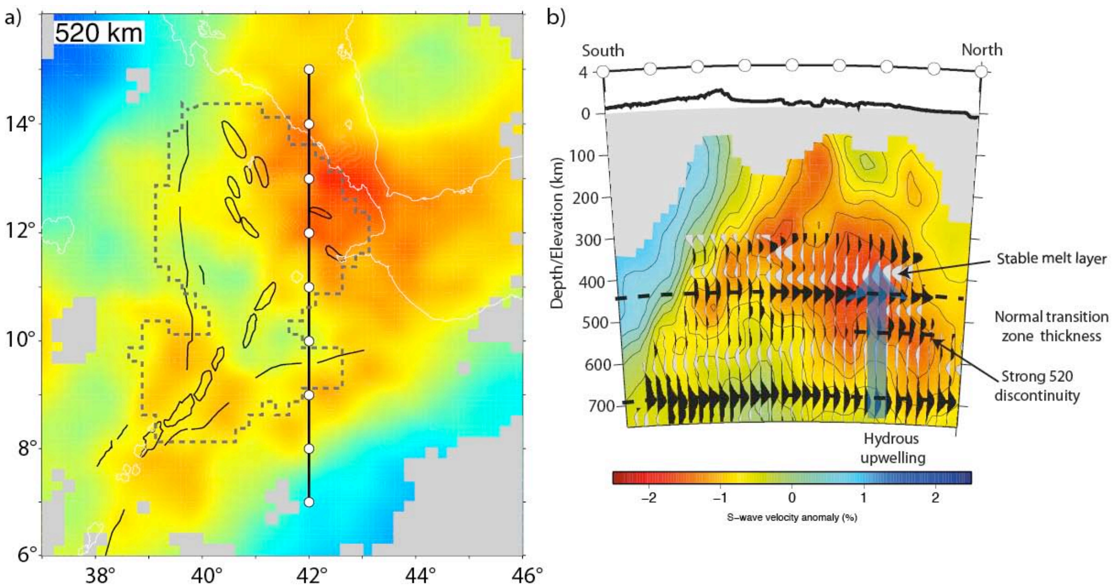

Figure 4: a) S-wave tomography at a depth of 520 km beneath the Horn of Africa. Dashed line shows region where transition zone thickness is similar to the global average (Thompson et al., in prep). b) Cross section showing S-wave velocity anomaly in the background with migrated receiver functions on top. Note the flat 410 and 660, sharp 520 and negative peaks coinciding with the lowest velocities.

Nabro Volcano

On June 12th 2011, Nabro volcano in Southern Eritrea erupted with little warning. This occurred just days before our deployment so, while we missed the initial eruption we managed to have our full network deployed within 10 days. This included a station just 30 km from the volcano (FAME). These stations, together with those deployed in Ethiopia and Djibouti allowed us to determine seismicity patterns in the time leading up to the eruption, and the days immediately following the eruption (Goitom et al., in prep). The eruption was preceded by just 5 hours of intense seismicity, with 2 earthquakes >5ML occurring either side of the eruption. Both Nabro and nearby Mallahle were seismically active during this time suggesting a linkage between the two via their magmatic system or thorough a change in stress brought on by the eruption of Nabro. Following the eruption volcanic tremor was seen across the stations in the Ethiopian network (GEF loan 885). Tremor continued until 16th June, followed by an increase in seismicity on the 17th June where the largest magnitude event was recorded (5.9M_L). Tremor picked up again following this intense seismicity. Correlating these tremor signals, particular at nearby station FAME will allow us to make comparisons with other datasets (e.g., Sulphur release, infrasound) to understand the dynamics of the eruption period. Data from FAME was also used in conjunction with a local array on Nabro Volcano (Hamlyn et al., 2014) (see GEF loan 953 report).

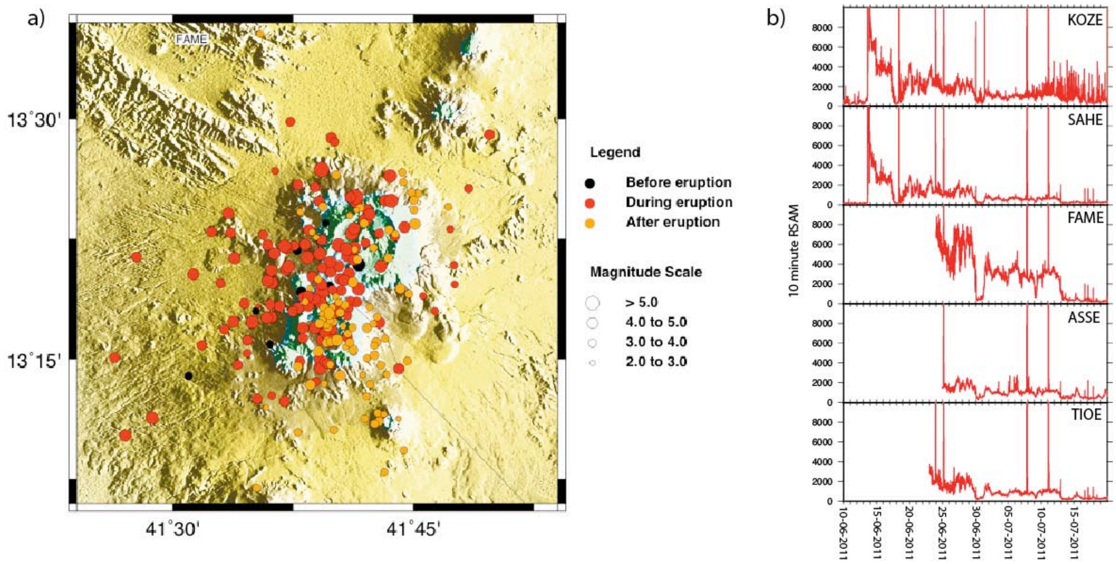

Figure 5: a) Seismicity located using the Ethiopian, Djibouti and Eritrean seismic stations from 23/02/2011 – 17/09/2011. b) RSAM (Real-time seismic amplitude measurement). Amplitude is summed across a 10-minute sliding window. High amplitudes show that volcanic tremor is occurring. KOZE and SAHE are Ethiopian stations.

Ongoing work

A number of studies involving the ESP datasets are ongoing. In particular, the data is being used in a regional Pn study to image the uppermost velocity structure to better understand the rifting process in the Red Sea/Gulf of Aden. Receiver functions will be analysed for crustal structure, building on previous work in Ethiopia (Hammond et al., 2013, Hammond, 2014) and Yemen (Ahmed et al., 2013). Also, shear-wave splitting studies will be conducted to understand the role that partial melt, mantle flow and fossilised structure play in driving rifting within East-Africa (see Hammond et al., 2014 for examples from Ethiopia). Also, the data is included in travel time inversions using data ranging from Saudi Arabia to Tanzania to allow high resolution images down into the lower mantle (Civiero et al., in prep).

Conclusions and recommendations

The GEF loan has led to the collection of an exceptionally high quality dataset in Eritrea. These are the first broadband seismometers ever deployed in the country. Following this project we are supervising an Eritrean PhD student (Berhe Goitom), the first in Earth Science since the country's independence. This shows the impact and capacity building potential GEF supported geophysical campaigns can have. Minimal problems were encountered during the deployment except for some power issues related to a faulty regulator at DOLE and an unknown issue at ASSE. The data have been crucial in tying together two other GEF loans, allowing us to image in high resolution the crust and upper mantle, and even the lower mantle, beneath the Afar triple junction. Results are showing how melt is important in driving rifting and that the mantle beneath Afar behaves much like an ocean-spreading centre. Results from ongoing studies are expected to provide more details on the processes during the final stages of continental break-up in the Red Sea/Gulf of Aden rifts.

Publications

Publications using these data have been highlighted in the reference list (in bold type). Other conference presentations describing the results have been made at 2011-2014 American Geophysical Union Fall meetings in San Francisco and European Geophysical Union meetings in Vienna as well as other small meetings such as the Asmara Geocongress

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