How does the Earth`s crust grow at divergent plate boundaries? A unique opportunity in Afar, Ethiopia

Abstract

In three field campaigns, we have acquired usable, generally high quality, magnetotelluric (MT) data at 40 sites, most with transient electromagnetic (TEM) data for static shift correction, over two magmatic segments in Afar, Ethiopia, a challenging fieldwork environment. Two profiles are across the rift axes and roughly orthogonal to them, one across a currently active segment, the other across an inactive segment. Activity on the former began in September 2005 with a volcanic eruption, the injection of a mega-dyke along the full 60 km long segment, 163 earthquakes with magnitude greater than 3.9, and over 8m of crustal movement. The third is an oblique profile towards the Dabbahu volcano that erupted in September 2005. In addition, we occupied a few sites to the north of the currently inactive segment, the final one as close as accessible to an area of rapid subsidence, thought to be deflation of a deep magma chamber filling a shallower chamber along the active segment to the north. After robust processing, dimensionality and geoelectrical strike direction assessment, static shift correction and rotation into geoelectrical strike co-ordinates, the MT data along the three profiles have been inverted for 2D models of resistivity beneath the profiles. The result for the first profile, across the active Dabbahu segment, was presented in the report on loan 855, along with background information on current activity on the segment. It can usefully be read in conjunction with this report, which therefore concentrates on the results from the other two profiles. In contrast to the Dabbahu segment model, the profile across the currently inactive Hararo segment is characterised by broadly resistive material in the sub-surface, suggesting an absence or only small quantities of melt in the sub-surface there. The model along the oblique profile indicates a very sharp contrast from relatively resistive material in the crust away from the volcano to the south-west to a very conductive sub-surface in the immediate vicinity of the volcano, to depths of approximately 35km. We interpret this to be a magma chamber beneath the volcano. The conductor extends to the south-west at sub-Moho depths, with slightly lower conductivities presumably indicating lower melt concentrations. The model agrees well with that for the Dabbahu segment at their point of intersection. We will be attempting 3D inversion of the full data set, though the distribution of sites is far from ideal for this. We have not yet undertaken a full sensitivity analysis of the models across the second and third profiles. The data from all three profiles are being interpreted in conjunction with other geophysical, geological and remote sensing data to understand the processes associated with continental rupture.

Background

The Afar region of Ethiopia is slowly rifting to form a new ocean. Much of the associated deformation and volcanism is concentrated along elongated magmatic segments, only some of which will be active at any one time (Figure 1). More details of and references to the tectonic background of the region are provided in the report on loan 855, hereafter referred to as Report 1. At the start of the project, our intention was to collect data along profiles across the currently active Dabbahu segment and currently inactive Hararo segment, to compare their geoelectrical structure. This was successfully achieved in 2008 and 2009 (green and blue points on Fig 2 respectively), though the most westerly site on the Dabbahu (2008) profile was poor quality. The interesting results from these two field campaigns and the identification of a new area of rapid subsidence to the north of the Hararo segment profile prompted our Consortium partners to devote extra funds to allow a third field season. The objective of the third campaign was to collect data as close as possible to the Dabbahu volcano, and towards the rapidly subsiding area at Saha, to the north of Semera and our profile across the Hararo segment. These sites are shown as red points on Figure 2. The profile in an approximately NNE direction towards the Dabbahu volcano will henceforth be referred to as the Teru profile. The poor quality data at the most westerly green point have not been used in modelling and interpretation, but have been replaced by those from the adjacent red point on the Teru profile.

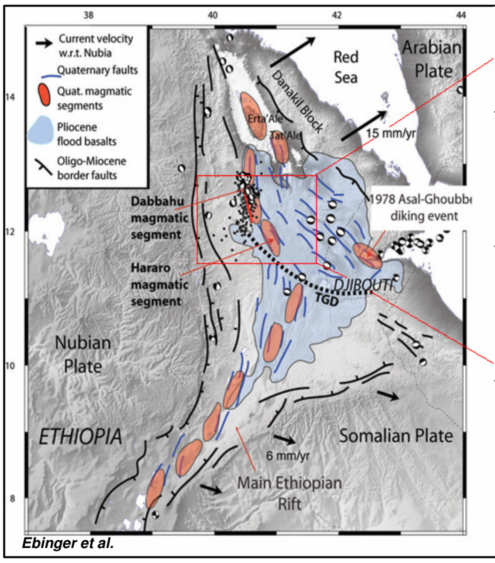

Figure 1. Tectonic setting of the area, after Ebinger et al. (2008).

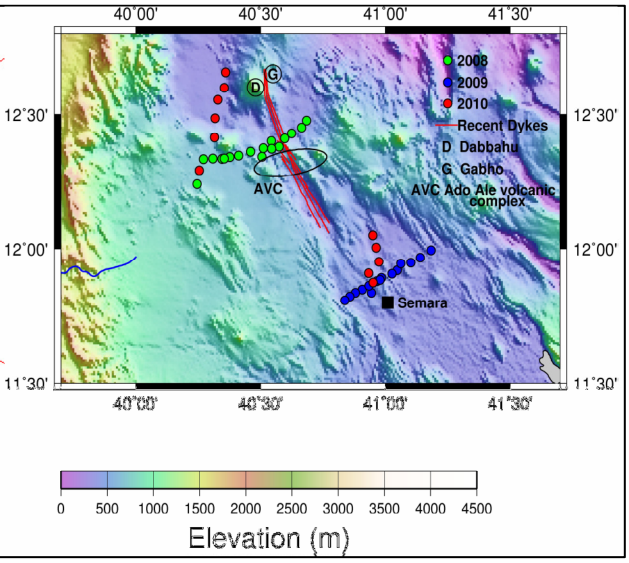

Figure 2. MT data acquired on the project, over the area of the red box in Figure 1. The blue points are referred to as the Hararo profile; the red points in the north-west of the region form the Teru profile.

Survey procedure

Most sites were occupied for 24-36 hours, aiming to provide MT periods down to ~1000s. Equipment failure and electrode noise spikes restricted the maximum period to less than this at some sites. Non-polarising electrodes were placed in a salty, bentonite mud to provide good electrical contact. Magnetic coils were buried to reduce noise. The last field season used coils loaned by the Geophysical Instrument Pool Potsdam, whereas the first two used GEF coils. We used a ‘plus sign’ configuration with electrode lines and coils orientated magnetic north-south and east-west. Electrode lines were about 100m long. We had 2-3 working sets of instruments at any one time, and at each site aimed to have synchronous recording with another site for part of the time to allow remote reference processing. TEM data were collected for static shift control, with a square loop of dimensions 100 x 100m and effective receiver loop size of 31.4m^2. The time rate of decay of magnetic flux was recorded over integration times from 0.25 to 120s. TEM data quality was uniformly good.

Processing and data quality

Data time series were robustly processed (Chave and Thomson, 1989) to provide impedance tensor estimates. We used a variety of algorithms to investigate the dimensionality of the data, including phase tensor analysis (Caldwell et al., 2004). Phase tensors ellipses by site and frequency were presented in Figure 3 of Report 1, where it was shown that a two-dimensional (2D) Earth approximation is adequate to explain most data. The same is true also of the data along the Hararo and Teru profiles. We used a variety of techniques to determine the geoelectrical strike direction, both on a site-by-site and period-by-period basis and using the ‘strike’ algorithm (McNeice and Jones, 2001), which finds the optimum strike angle for all sites and periods. This gave strike directions of 327.5° and 315° for the Hararo and Teru profiles, respectively. The Teru profile is somewhat oblique to the rift axis, but the swing to the NW from the 340° strike direction of the Dabbahu profile (Report 1) means that 2D inversion is still feasible. As for the Dabbahu profile, the strike direction of the Hararo profile matches the rift axis.

Static shift from galvanic distortion owing to small-scale, shallow conductors can lead to erroneous structure at all depths within MT models. Without independent control on the shallow structure such as provided by TEM data, the MT apparent resistivity (ρ_a) curve shifts are unknown. The TEM data were processed and modelled using Aarhus Geophysics SiTEM/Semdi software. The delay times from the processed TEM decay curves were turned into equivalent MT period (Sternberg et al., 1988); curves were then matched to the actual MT ρ_a curves. The period overlap was small, but sufficient to determine static shifts in most cases. We found examples where both ρ_a MT curves needed shifting to match the TEM data curves, as well as the more usual situation where one or other mode ρ_a curve was moved up or down to match the other. An example is shown in Figure 3.

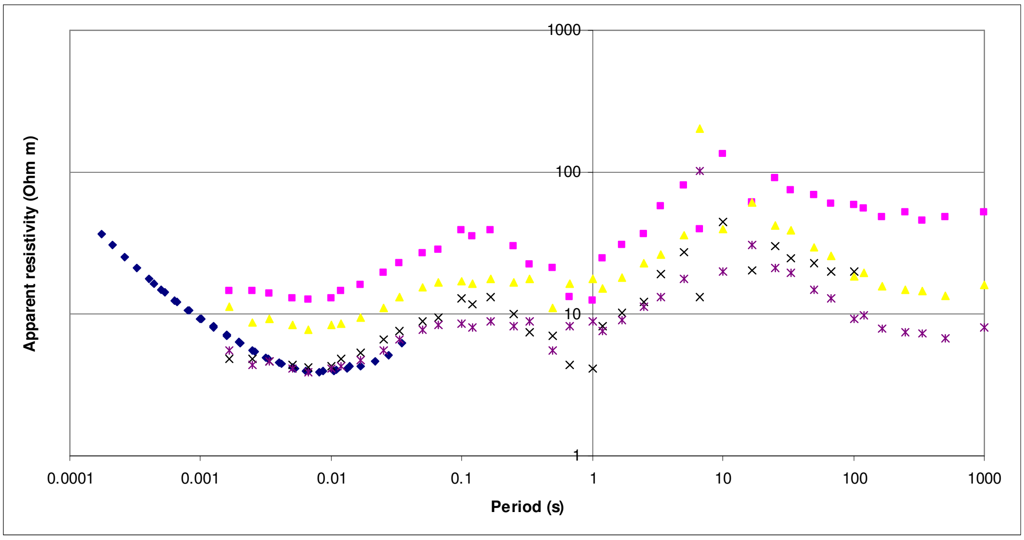

Figure 3. Example of static shift correction; site 910, Hararo line. TEM times are scaled down by a factor of 200 to convert to equivalent MT period (Sternberg et al., 1988). Black diamonds are scaled TEM data; red squares are original TM ρ_a data; yellow triangle, original TE ρ_a data; crosses, corrected TM ρ_a data; asterisks, corrected TE ρ_a data.

The MT data can also be corrected for static shift by solving for the parameters of an assumed distortion model while determining the electrical strike direction (McNeice and Jones, 2001); the results of the two methods agree well. The data were finally run through a ρ^+ consistency check (Parker and Booker, 1996). Examples of the corrected and rotated data are presented on a site-by-site basis in Figures 6 and 7.

Modelling

A 2D model space beneath each profile was parameterised into blocks of constant resistivity, with a variable block size represented the decreasing resolution of the data with depth and the site distribution, and was overlain by 10 air layers, following accepted guidelines. The Hararo profile mesh contained 3640 cells, approximately 2300 of which were beneath the profile, whose values were obtained using the 2D REBOCC algorithm (Siripunvaraporn and Egbert, 2000) from 535 data points, covering a frequency range 833 to 10^{-3} Hz. With an error floor of 10%, the root-mean-square (rms) misfit was 2.35. The Teru profile model was obtained from 289 data covering a frequency range 8402 to 10^{-3} Hz. The model had 2065 cells, approximately 1070 of which were beneath the profile. The rms misfit in this case was 3.06 (10% error floor), from 289 data points. The models are presented in Figures 4 and 5, the data and their predictions by the models in Figures 6 and 7.

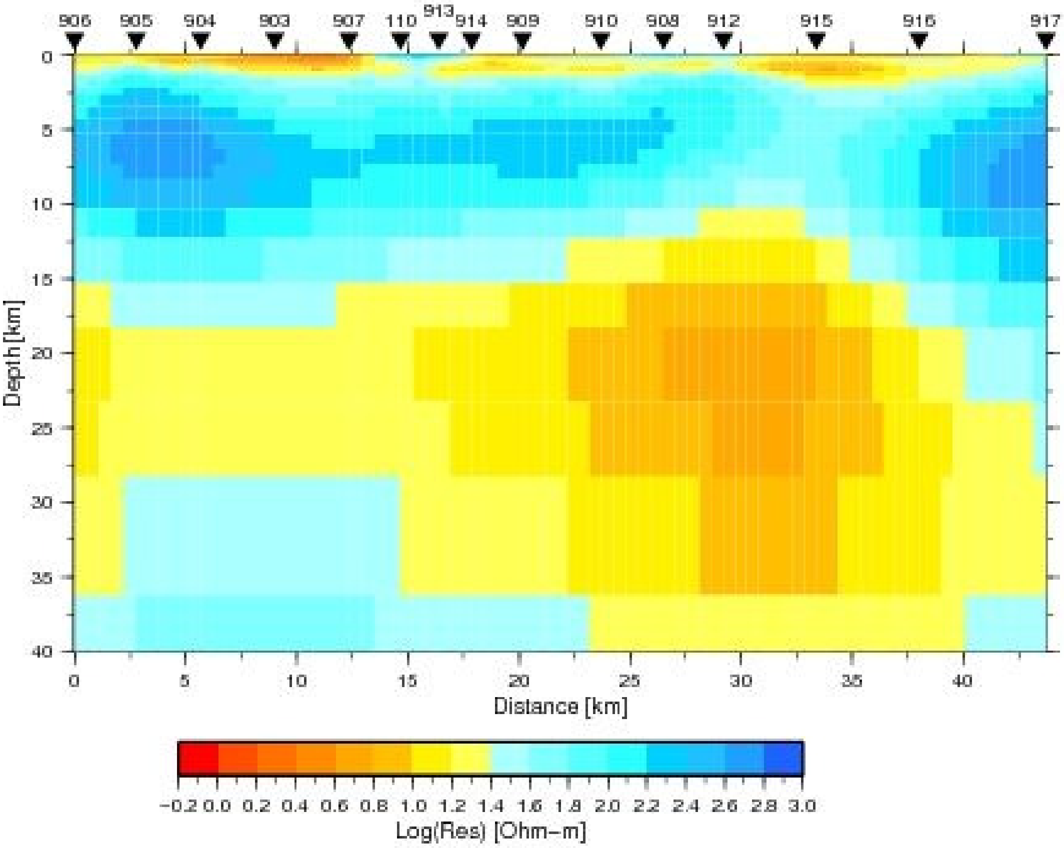

Figure 4. Model along the Hararo profile, from south-west (left) to north-east (right). The lower crust and upper mantle are much less conductive than beneath the Dabbahu and Teru profile models (Report 1 and Figure 5 respectively).

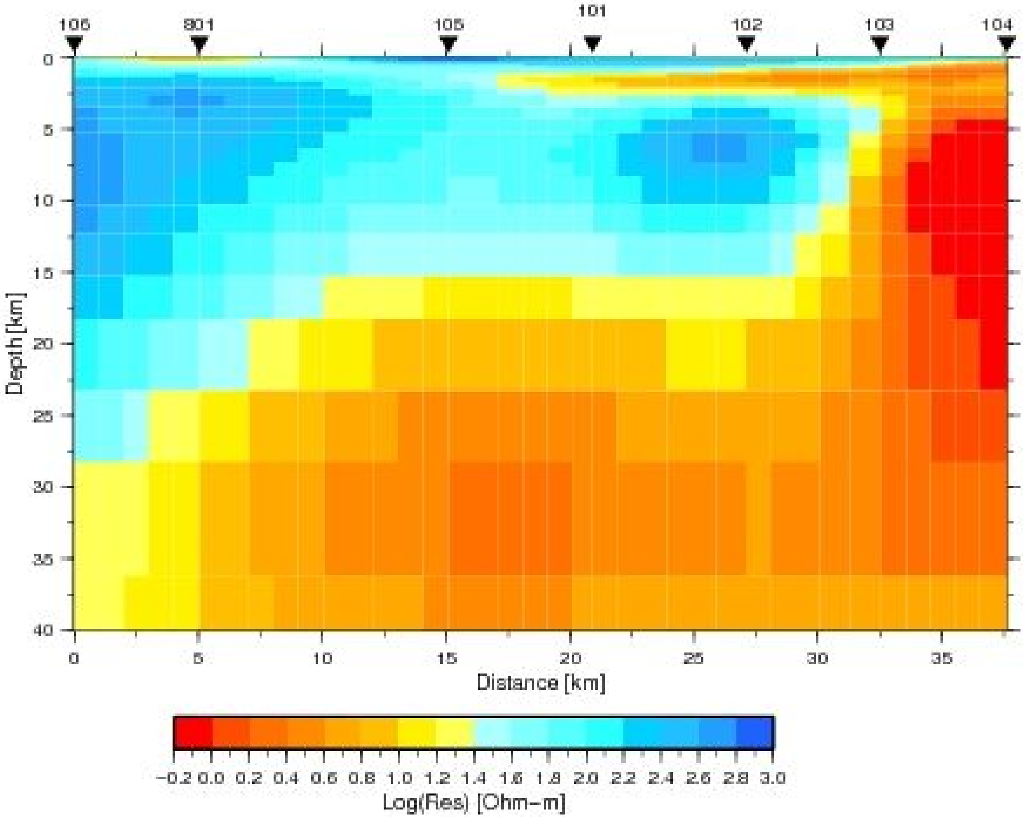

Figure 5. Model along the Teru profile, from SSW (left) to NNE (right), using the same colour scale as in Figure 4. Note the particularly conductive shallow sub-surface close to the Dabbahu volcano.

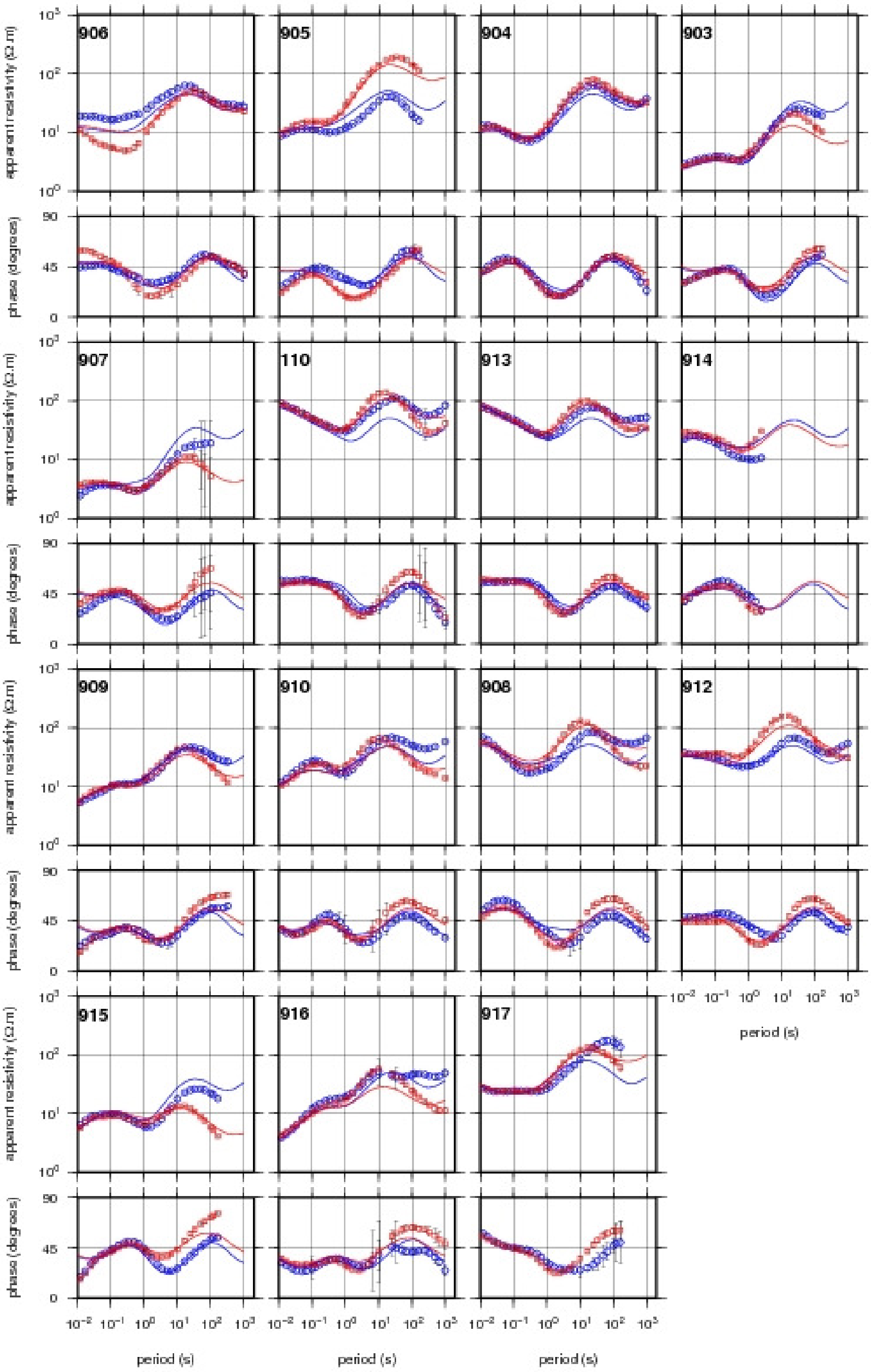

Figure 6. Hararo profile MT rotated data curves and model predictions for model shown in Figure 4, from left to right across the model. Red points and lines: TM mode; blue points and lines: TE mode.

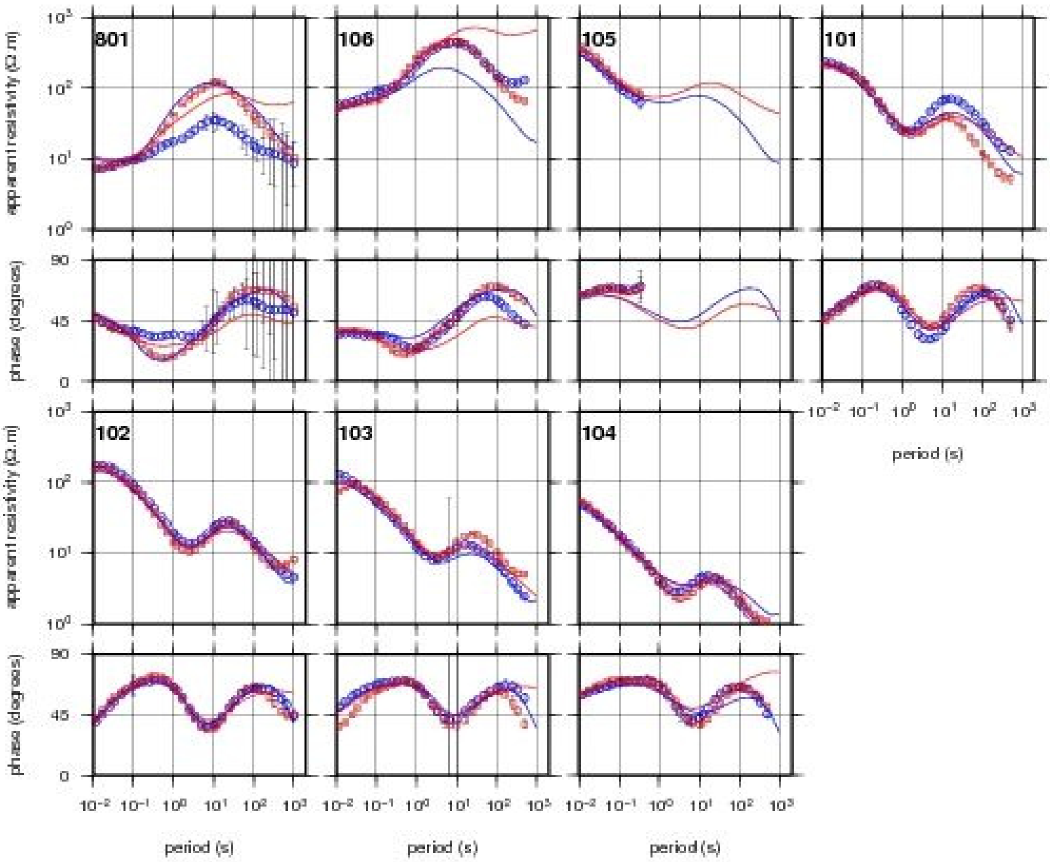

Figure 7. Teru profile MT data curves and model predictions for model shown in Figure 5, from left to right across the model. Red points and lines: TM mode; blue points and lines: TE mode.

Interpretation to date and preliminary findings

There is a good contrast in the deep resistivity structure beneath the active Dabbahu and inactive Hararo magmatic segments, with a suggestion of much less partial melt/magma beneath the latter. However, the increase in conductivity to values indicative of partial melt begins at similar depths – about 10km – beneath both segments. The Hararo sub-crustal conductor is offset slightly to the east of the rift axis, which is centred on site 913. One of our site guards felt an earthquake when at an easterly site overnight, although we have no real indication of its location, and whether it was associated with magma movement beneath. The most conductive part of the region is in the mid-crust near the Dabbahu volcano, indicating large volumes of partial melt (~60%, even using the conservative continuous parallel melt pathways estimate appropriate for oriented melt pockets (Roberts and Tyburczy, 1999), which may not be appropriate for a magma chamber; the Hashin and Shtrikman (1962) upper bound gives ~70%). The indications are there is magma throughout the crust and upper mantle beneath the volcano. As with the Dabbahu profile in Report 1, there is a good conductor in the near surface (top ~2 km) beneath the Hararo profile, which again is most likely representing saline fluids.

Report 1 suggested the sub-crustal conductor beneath the Dabbahu profile extended to the maximum penetration depth of the data. However, the data sense the base of the conductor, as can be seen from the decreasing phase at periods > 100s and the longest period apparent resistivities at some sites. It is difficult to put a reliable depth on its base, since REBOCC tends to smear the structure with depth to minimise the model roughness, but tests where a resistive half space terminated the model, whose top surface depth was varied, suggests a depth of 30-40 km, the shallower depth providing a better fit to the data from the eastern part of the profile.

Conclusions and further work

MT with TEM for static shift control and robust processing has produced an excellent data set in the harsh and difficult conditions of Afar. 2D inversion indicates large areas of high conductivity in the sub-surface beneath the Dabbahu magmatic segment, and considerably smaller volumes beneath the Hararo magmatic segment. The data can be reconciled with those from other studies and provide the first direct evidence for a deep magma chamber beneath the Dabbahu segment, indicated by its high electrical conductivity. In contrast, there is considerably less magma beneath the inactive Hararo segment. This is much as expected, but it is good to have confirmation. Although there has been no further surface eruption of the Dabbahu volcano since September 2005, the MT results suggest a significant magma chamber exists beneath it, indicating an on-going hazard.

Further work will include analysis of the short line towards the region of rapid subsidence around Saha, to see if there is support for the hypothesis that a magma chamber there is emptying to fuel dyke injection in the Dabbahu segment. We also intend to undertake 3D inversion of the full dataset. Analysis of our results in conjunction with other data collected in the Consortium is underway. For example, Keir et al (2011, in press) interpret crustal seismic anisotropy close to the rift axis as resulting from a combination of an increased density of dyke-induced faults and oriented melt pockets near volcanic centres. A Fulbright-funded student will start a Masters by Research project in Edinburgh in September, concentrating on how electromagnetic data can be combined with seismic data to assess geothermal potential. We now have the latest results from the continuing Tendaho geothermal project being undertaken by BGR, Hanover, which will contribute to this study.

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Acknowledgement These GEF loans were supplemented by equipment loaned from the Geophysical Instrument Pool Potsdam (part of GeoForschungsZentrum)