A 3D Hypothesis Test for the Kenya Rift

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Abstract

Analyses of magnetotelluric (MT) and magnetovariational (MV) data from 20 sites spanning southern Kenya has revealed significant three-dimensional effects.

Consideration of both regional geology and induction arrow transfer functions implies the importance of two principal strike directions: One delineated by the N-S trending rift, the other controlled by a continental scale, Protorozoic, NW-SE striking, fault fabric. The hypothesis that the induction arrows might be explicable in terms of the near-surface expression of the conductive infill of the rift, together with a deep-seated, NW-SE striking conductor extending into the upper mantle is borne out by three-dimensional modelling. Spatially and directionally, the mantle conductor may correspond with a low velocity zone modelled from teleseismic data and both geophysical signatures may relate to a major, NW-SE striking shear zone system which has been mapped at the surface.

A low velocity zone modelled from seismic refraction data recorded along a profile which crosses the rift at the same latitude as the MT measurements has been speculatively attributed to a few percent partial melt in the mantle directly below the rift. No support for this interpretation is provided by the MV data.

Introduction

In early 1995, broad-band magnetotelluric (MT) and transient electromagnetic (TEM) data were collected at 20 sites in southern Kenya Details of site locations and instrumentation can be found in Simpson et al. (1996).

This contribution deals principally with the MV data. More detailed discussion of the MT data will appear in Simpson et al (1997).

The two profiles - one of approximately 400 km length (from 0.95° S, 34.21° E to 2.50° S, 37.75° E) and the other of approximately 200 km (from 1.51° S, 37.09° E to 3.53° S, 38.39° E) - along which sites were located traverse several tectonic units, including (from west to east) the Protorozoic collision zone between the Nyanza craton and Mozambique belt, the Kenya rift and the Chyulu Hills, a Holocene, NW-SE striking, volcanic chain. The rift is crossed at latitude 1.81° S, where it is 60km wide and its western boundary is flanked by a 1500m escarpment. Seismic and gravity models are pre-existent for both profiles.

Electromagnetic data can provide constraints on physical properties and states (e.g. melt distributions) within the crust and mantle. Such knowledge is paramount to understanding rifting.

Induction arrows

As far as 100 km to the west of the rift, the real, Parkinson induction arrows at 40 seconds (figure 1a) point in an almost perpendicular sense to the N-S trending rift, reaching their maximum magnitude of 0.86 at Ngurumani (1.81° S, 36.05° E), just within the rift. At Magadi (1.87° S, 36.26° E), approximately on the rift axis, the induction arrows rotate to approximately ESE-WNW, and at Singlraine (1.90° S, 36.50° E), nearer to the eastern flank, they are oriented in a SE-NW direction.

In the Chyulu Hills region (2.5° S, 37.75° E to 3.05° S, 38.11° E) the induction arrows become rather small and no dominant or stable inductive strike direction is perceived. The lengths of the imaginary induction vectors are comparable with those of the real vectors, whilst their respective azimuths differ significantly from the parallel/anti-parallel sense. In contrast, on the western side of the rift, the imaginary components of the induction vectors are generally much smaller than the real components. Induction arrows to the east of the Chyulus are probably effected by the ocean.

At 1000 seconds, the azimuths of the real induction arrows to the west of the rift are very consistent, rotating slightly within the rift and for the two stations immediately to the east of the rift, but preserving an approximately collinear, SW-NE to SSW-NNE orientation (figure 1b). This trend is also reflected in surveys reported by Rooney and Hutton (1977), Banks and Ottey (1973), Beamish (1977) and Hutton et al. (1989), conducted further to the north, nearer to the equator. The magnitudes of these induction arrows is rather large (e.g. 0.69 at Ngurumani (1.81° S, 36.05° E) just within the rift; 0.75 at Selengei (2.18° S, 37.19° E), approximately 60 km to the east of the rift)

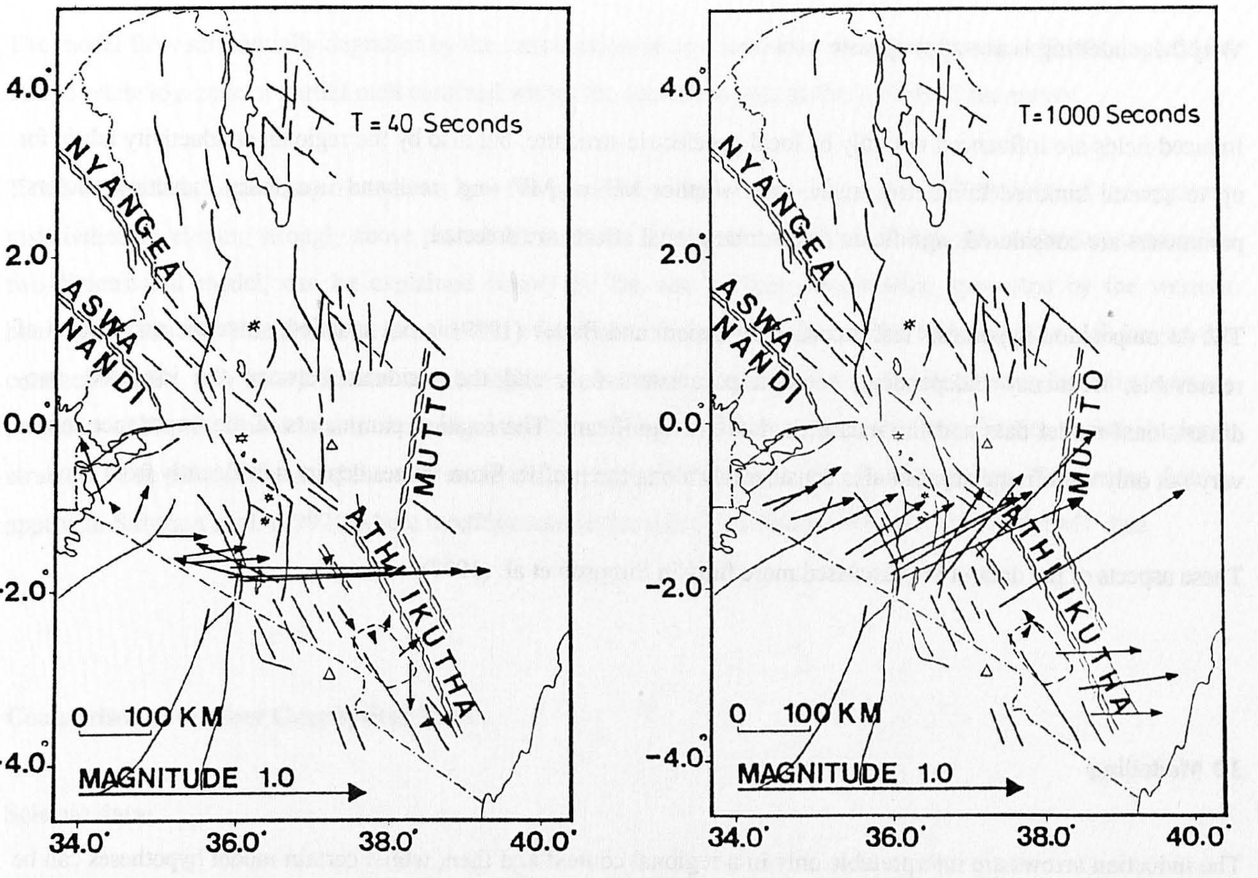

Figure 1 Real Parkinson induction arrows at (a) 40 seconds and (b) 1000 seconds, superimposed upon the regional fault fabric (redrawn from Smith and Mosley, 1993). Labels indicate NW-SE striking shear zones. The region encompassed by the dashed lines to the east of the rift is the Chyulu Hills.

Nearer to the equator, the induction arrows mapped by Beamish (1977) are smaller and reverse direction on the eastern side of the rift, pointing back towards the rift axis. These arrows are probably influenced by an anomaly beneath the Kenya Dome (Beamish, 1977) which the rift bisects and where partial melt is believed to occur within the upper mantle (e.g. Mechie et al., 1994). Meanwhile, the induction arrows from the present dataset are not influenced in an obvious manner by partial melt directly below the rift. Rather, their large magnitudes and orientations indicate a significant conductivity contrast to the east of the rift.

At 100 seconds, the azimuths of the real induction arrows lie between those at 40 and 1000 seconds and are probably influenced both by the currents channelled along the rift and those governing the longer period induction arrows.

The induction arrows considered resolve no obvious contact between the Nyanza craton and Mozambique belt where the suture zone is believed to be crossed (Shackleton, 1986).

Why 2d modelling is not appropriate

Induced fields are influenced not only by local geoelectric structure, but also by the regional conductivity fabric for up to several hundred kilometres away, and whether MT or MV (e.g. real and imaginary induction vectors) parameters are considered, significant three-dimensional effects are detected.

The decomposition hypothesis test proposed by Groom and Bailey (1989) is not satisfied, since the assumption of retrievable, frequency independent, rotation parameters fails and the residuals between the idealised, two-dimensional model data and the measured data are significant. The rotation parameters of the impedance tensor vary not only with frequency, but also considerably along the profile. Skew values depart significantly from zero.

These aspects of the dataset are discussed more fully in Simpson et al. (1997).

3D Modelling

The induction arrows are interpretable only in a regional context and then, whilst certain model hypotheses can be shown to be false, others cannot be proven unequivocally to be true, but only to lie within the group of *possible* models which further surveys might be designed to constrain.

3D modelling, employing the GEOTOOL'S implementation of Mackie et al.'s (1993) finite difference code, suggests that the observed trends in the induction arrows can be explained in terms of the near-surface, conductive expression of the rift and a more deep-seated, NW-SE striking conductor, which *may* be related to a broad, NW-SE striking, composite, Protorozoic, shear zone system. Resistivities within the rift are between 5-50 Ohmm. The conductance is asymmetrically distributed, with the western half of the 60 km wide rift required to be more conductive than the eastern half.

Given the inherently poor vertical resolution of MV data, ambiguities exist concerning the depth, thickness and conductivity of the NW-SE striking conductor, but it is required to extend at least into the upper mantle. With consideration to the periods affected, a good fit is obtained for a conductor of between 0.5-5 Ohmm extending from 30 to 60 km, implying a conductance of several thousand Siemens. The orientations and relative magnitudes of the real induction arrows are well-explained by this model (the maximum angular deviation between modelled and measured induction vectors is within 5^{o} for all except the 3 most westerly sites along the cross-rift profile), but the absolute magnitudes of the modelled induction vectors are about a factor of two smaller than the observed ones.

The model fit is substantially degraded by the introduction of any conductor directly below the rift which could be said to relate to a zone of partial melt confined within the sub-rift mantle at the latitude of the survey.

Three-dimensional modelling also shows how the pronounced splitting (of the order of 3 decades) of the apparent resistivities developing strongly above periods of 1 second at Ngurumani, which is inexplicable by any reasonable two-dimensional model, can be explained simply by the near-surface discontinuity generated by the western boundary of the rift. This boundary is modelled a few hundred metres to the west of Ngurumani, which lies on the conductive side. Any interpretation which neglected the sharp electrical discontinuity arising from the western boundary of the rift would lead to the assignation of resistivities deviating severely from the true resistivity depth structure. The eastern flank of the rift, meanwhile, appears to be less-sharply accentuated. Supporting figures appear in Simpson et al. (1997), where modifications to the model are discussed in the light of the MT data.

Comparison with other Geophysical Data

Seismic data

Seismic studies indicate the presence of a steep-sided, low-velocity zone (7.8 km/s) within the mantle directly below the rift. This was initially ascribed to the presence of partial melt (Birt et al., 1996), an interpretation which is not supported by the electromagnetic model studies; whilst consideration of ternary diagrams relating P-wave velocities and isotopic mineral compositions for different in situ temperatures, indicates that for elevated temperatures, P-wave velocities of 7.8 km/s can be obtained without partial melt occurring. Furthermore, the modelled seismic velocities are poorly constrained and whilst the velocity of 7.8 km/s produces the best fit to the data, velocities of between 7.7-8.0 km/s "can also fit the data to within acceptable limits" (Birt et al., 1996). Comparing the seismic velocity model of Birt et al. (1996) for the cross-rift profile with a previous model generated from seismic data recorded along an axial profile (Mechie et al., 1994), indicating upper mantle velocities of 7.5km/s below the southern rift, however, raises the possibility of seismic anisotropy, which a dyke model might explain (Simpson et al., 1997).

If partial melt is present, then the concentration is insufficient to exceed the critical limit to form extensive connections, a necessary condition for it to be imaged as a conductor.

Further to the north, where sub-rift mantle velocities of up 7.6 km/s, rising to 8 km/s on the rift flanks are modelled, 3-5 % partial melt is required in the mantle (Mechie et al., 1994). Our NW-SE striking conductor may cut the rift in this region. Furthermore, a NW-SE striking, upper mantle, low velocity zone, ascribed to 3-6%

partial melt concentrated within the Aswa-Nandi/Nyangea-Athi-Ikutha shear zone system, has been modelled from seismic tomography data (Achauer, 1994). A reversal and reduction in magnitude of the induction arrows of Beamish (1977) on the eastern side of the rift, nearer to the equator, might also be explained by this model.

At about 10km depth, there is a strong reflector which is interpreted as fluid around the brittle-ductile transition. Meanwhile, whereas it is often said that around the brittle-ductile transition there exists a correlation between conductivity anomalies and reflection anomalies, there is no convincing evidence for a good conductor at this depth.

Discussion and Conclusions

In the environs of the Kenya rift induced electromagnetic fields can be shown to be influenced by three-dimensional effects. In addition to the rift, which strikes approximately N-S, geologists recognise a continental scale, NW-SE trending Protorozoic fault fabric which pre-dates rifting (Smith and Mosley, 1993). The rift floor itself is intersected by numerous, sub-parallel, NW-SE striking faults and prominent, NW-SE striking, composite shear zones extending for hundreds of kilometres are clearly imaged in satellite data.

Induction arrows from the environment of the Kenya rift indicate the presence of two dominant conductive signatures. Three-dimensional modelling shows that these can be explained in terms of (i) the near surface expression of the conductive sedimentary infill of the N-S striking rift and (ii) a deep-seated, NW-SE striking conductor extending into the mantle. This second conductor is directionally coincident with the Aswa-Nandi/Nyangea-Athi-Ikutha shear zone system. Smith and Mosley (1993) consider this broad zone of NW-SE striking, composite shear faults, which pre-dates rifting, as a feature of lithospheric extent and have suggested that as a zone of anisotropic mechanical weakness it may have played an important role in controlling rift architecture and evolution, as well as providing weak conduits for the ascent of magma. However, the apparent spatial correlation between this NW-SE trending shear zone, a NW-SE striking seismic low velocity zone in the upper mantle and a possible NW-SE striking upper mantle conductor may be circumstantial only. To date there exists no unequivocal evidence for the existence of shear zones in the upper mantle, which is normally assumed to deform by pure shear.

Interpretation of the NW-SE striking conductor in terms of partial melt would require temperatures in excess of 1200^{o}C (Waff, 1974). The high standard deviation associated with surface heat flow measurements in the region (given by Morgan (1982) as 105 $^{+}/_{-}$ 51 mWm^{-2}) rules out meaningful comparisons, since no data exists for the area to the east of the rift directly over the proposed conductor.

Whilst an earlier seismic study crossing the rift at the same latitude as the MT measurements implied the presence of a low velocity zone, which was speculatively attributed to a few percent partial melt in the mantle directly below the rift, unequivocal support for this interpretation is not provided by the MV data.

A possible conductor below the Chyulu Hills, where a seismic anomaly has been ascribed to partial melt requires further study. However, further three-dimensional model calculations are not considered propitious in relation to the significance of the final model, given the limitations of the data set.

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