KENYA RIFT STRUCTURE FROM GEOPHYSICS

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Summary.
Seismic refraction/wide-angle reflection experiments show major crustal thickness variations along and across the Kenya rift. Along the rift axis the crustal thickness changes from 35 km beneath the Kenya dome to 20 km beneath Turkana in the north. Below the whole of the 600 km long axial rift profile, P_n velocities are low being 7.5-7.8 km/s. Profiles across the central and southern parts of the rift north show that this low mantle velocity and crustal thinning up to 10 km are confined to below the surface expression of the rift. Abrupt changes in Moho depths and P_n velocities occur as the rift boundaries are crossed. Beneath the rift flanks normal P_n velocities of 8.0-8.3 km/s occur. The above results taken together with those from teleseismic studies, gravity, MT, petrology and surface geology indicate anomalously hot mantle material appearing below the present site of the Kenya rift about 20-30 Ma ago. This gave rise to volcanism along the whole length of the rift and modification of the underlying crust by mafic igneous underplating and intrusion.

The Kenya Rift Geology and the KRISP seismic profiles

The Cenozoic East African Rift System extends for over 3000 km from the Afar triple junction in the Gulf of Aden to the Zambesi River in southern Africa and is one of the finest examples of a present-day continental extension system. It cuts through Proterozoic basement and splits into two branches around the East African Plateau, the elevated rocks of the Archean Nyanza Craton, thought to overlie an upwelling mantle plume. There is a strong association of earthquakes and volcanoes with the rift zones. The Kenyan segment of the system traverses the country from north to south in a series of alternating polarity half-grabens, 50-100 km wide. It is particularly well-developed across the Kenya Dome, a local uplift in the central region where the rift floor reaches a maximum elevation of 1800m and falls to 400m in the north and 600m in the south. Fault scarps get up to 1600 m in this region. The rift zone widens and becomes more diffuse north and south of the dome. Cenozoic volcanic rocks (associated with the rifting event) and recent sediments cover large parts of central and eastern Kenya overlying Precambrian basement. The rift has developed close to the boundary between the Archean Nyanza Craton in the west, and the Proterozoic Mozambique Belt which is thought to record a collision with the craton from the closure of the late Precambrian Mozambique Ocean.

Rift activity started in the Oligocene in northern Kenya with the eruption of flood basalts. The Kenya Dome was uplifted by about 1 km prior to the initiation of magmatism in the rift in the early Tertiary. At this time, the central rift was a site of extensive eruptions of phonolites from fissures. The first major rift faults developed in the mid to late-Miocene. More recently, trachyte, basalt-trachyte and phonolite caldera volcanoes have built up on the floor of the rift, along with the formation of a series of major volcanic centres on the eastern flank of the rift, including Mt. Kenya, the Chyulu Hills and Mt. Kilimanjaro in northern Tanzania.

Geophysical models based on gravity and teleseismic studies suggested attenuation of the lithosphere and the rise of anomalous low-velocity, low-density asthenospheric material to near the base of the crust beneath the Kenya Rift. This process was also suggested as the mechanism of isotatic compensation for the raised topography of the Kenya dome. The models also predicted a relatively dense, intrusive body penetrating the crust to high levels above the anomalous mantle zone beneath the rift axis.

However, the few seismic refraction and earthquake data collected in the late sixties and seventies did not adequately constrain the models developed from gravity. The need for high-resolution seismic studies to investigate the deep structure of at least one continental rift was noted at various international meetings in the early eighties. It was particularly emphasised at the 1981 NASA-AGU discussion meeting held in the Napa Valley, California, on Lunar and Planetary Rifting, following the appearance of rift-like features on other planets. The proposal for an international project to investigate the Kenya rift emerged from that meeting.

In 1990, seismic refraction investigations were carried out along three lines in five deployments, A-E. Deployments A-C were along a 750 km long N-S axial rift line, D along 450 km E-W cross-rift line north of the Kenya dome, and E along a 300 km northeast flank line. In 1994, two further deployments F-G were investigated. F was along a 420 km long line crossing the Chyulu Hills Quaternary volcanic field on the southeastern flank of the Kenya rift. G was along a 430 km long cross-rift line south of the Kenya dome. During the earlier test phase of the project in 1985 a an axial line extending from Lake Baringo to Lake Magadi was investigated as well as a short cross-rift line just north of the Susua volcano.

Structure of the crust and uppermost mantle under the Kenya rift

The most important features derived from the KRISP '85, KRISP '90 and KRISP '94 data are the crustal thickness variations both along and across the rift and the distribution of upper mantle velocities beneath the rift. Crustal thickness changes dramatically along the rift by 15 km from about 35 km in the south beneath and to the south of the Kenya dome to around 20 km in the north beneath the Turkana region. This is accomplished to a major extent by the thinning of the 6.8 km/s basal crustal layer from about 9 km in the south to 2 km in the north. There is also a correlation between crustal thickness and topography, rift width, surface geological estimates of crustal extension and Bouguer anomaly.

Beneath the Kenya dome in the south the crust is thick (35 km), the rift elevation is high (2-3 km), the rift is narrow (50-70 km wide) and well-defined, surface estimates of extension are small (5-10 km) (Baker and Wohlenberg 1971, Strecker 1991) and Bouguer anomalies are low (-200 to -250 mgal). Towards the north beneath Turkana the crust thins to 20 km, the rift topography decreases to about 400 m, the rift widens to 150-200 km, surface estimates of extension increase to 35-40 km (Morley et al. 1992), and the Bouguer anomaly increases to about -50 mgal. The regional 150-200 mgal change in Bouguer anomaly can be completely explained by the change in crustal thickness along the rift axis (Mechie et al. 1994a). Along the northeastern flank profile between Turkana and Archers Post the crustal thickness decreases from 35 km under Archers Post to about 29 km just east of the rift (Prodehl et al. 1994b), at the latitude of Lokori in the rift where the crustal thickness is already only 20 km. As the northeastern flank profile lies between the Anza graben to the northeast and the Kenya rift to the southwest the thinning beneath the axial rift profile with respect to that beneath the northeastern flank profile must be due to the Tertiary rifting episode.

Across the rift at the latitudes of both cross-rift lines D and G, crustal thinning and the low uppermost mantle P_n velocities of 7.5-7.8 km/s are restricted to below the surface expression of the rift. As soon as the rift boundaries at the surface are crossed at depth the crustal thickness and the P_n velocities increase abruptly. Beneath the rift flanks, except beneath the Chyulu Hills area, the P_n velocities have normal values of 8.0-8.3 km/s. Teleseismic studies show that the abrupt change in upper mantle velocities as the rift boundaries are crossed persists down to 100-150 km depth (Achauer et al. 1994). Beneath the Quaternary volcanic field of the Chyulu Hills the P_n velocity is 7.9-8.0 km/s. Along the cross-rift profile D at the latitude of Lake Baringo about 100 km north of the Kenya dome the crustal thinning below the rift is 5-10 km. In contrast, along the cross-rift profile G at the latitude of Lake Magadi about 100 km south of the dome, it is somewhat less at about 2-3 km. Further, the crustal thinning beneath the Lake Magadi portion of the rift south of the dome is flanked by thicker crust to the east (38-44 km) than to the west (< 35 km) where the major Nguruman fault bounding the rift is located. This is in contrast to the situation below Lake Baringo north of the dome where the crust on either side of the rift tends to be more equal in thickness or to be thicker beneath the western flank (Braile et al. 1994, Maguire et al. 1994) where the major Elgeyo fault bounding the rift is found. Below the cross-rift profile south of the Kenya dome, relatively thin crust (< 35 km) was found west of the rift all the way to Lake Victoria (Birt et al. 1997). East of the rift, some of the thickest crust observed so far beneath Kenya (38-44 km) extends eastwards for over 300 km from the Lake Magadi region to beyond the Chyulu Hills/Kilimanjaro region (Novak et al. 1997a).

Discussion and Conclusions

The fact that volcanism precedes faulting in both the northern and southern parts of the rift by a few million years (Morley et al. 1992, Smith 1994) plus the fact that the stretching (β) factor does not exceed 1.7 anywhere along the rift provides evidence that much of the volcanism has been generated by melting of the mantle at anomalously high temperatures (Hendrie et al. 1994).

The petrological interpretation of the uppermost mantle seismic velocities indicates that the depth to the onset of melting below the Kenya dome in the southern part of the rift is 50 + 10 km (Mechie et al. 1994b).

The above summary of the results from the KRISP '85, KRISP '90 and KRISP '94 seismic refraction/wide-angle reflection experiments together with the results from the teleseismic studies, petrology and surface geology provide the basis for the following evolutionary and present-day structural summary. Anomalously hot mantle material migrating southwards from the mantle plume centred under Afar (northern Ethiopia) began to rise below northern Kenya and gave rise to the volcanism about 30 Ma ago in the northern part of the rift in the Turkana region. Between 30 and 25 Ma ago faulting, extension and associated crustal thinning began in the northern part of the rift and, according to Hendrie et al. (1994), 12-13 km surface extension had occurred by the end of the Palaeogene, 23.5 Ma ago. During the Lower and Middle Miocene faulting, extension and crustal thinning continued in the northern portion of the rift and, essentially by 10 Ma ago, 25-30 km of surface extension had taken place in the north. The magmatic event which occurred between 23 and 14 Ma ago and which produced a phase of alkaline basaltic volcanism in the northern part of the rift was probably responsible for a phase of magmatic underplating and intrusion in the southern part of the rift (Hay et al. 1995a). This magmatically underplated and intruded material was, in turn, the source for the extensive flood phonolites which erupted in the southern part of the rift between 14 and 11 Ma ago (Hay and Wendlandt 1995, Hay et al. 1995b). In the south in the period 16-20 Ma ago volcanism began, probably associated with the active uprising of mantle plume material below the Nyanza (Tanzanian) craton and extending to beneath the present site of the Kenya dome. Faulting, extension and crustal thinning began in the southern part of the rift at around 10 Ma ago. Around 10 km of surface extension has occurred in both the northern and southern parts of the rift in the past 10 Ma. Thus a total of 35-40 km surface extension has occurred in the northern part of the rift where the crust is now only 20 km thick. In contrast, the much smaller amount of surface extension in the southern part of the rift is associated with a present-day 35 km thick crust.

The active uprising of anomalously hot mantle material beneath the Kenya rift for the past 20-30 Ma and the associated faulting, surface extension and crustal thinning has given rise to the present-day structure.

Magmatic activity associated with the rifting process has also modified the crust. It is estimated that at least 3-4 km of the 9 km thick basal crustal layer beneath the Kenya dome is due to mafic igneous underplating and intrusion during the rifting process. In addition a dyke injection zone in the central 40 km of the rift penetrating both the upper and lower crust is proposed to explain the axial gravity high (Swain 1992). Crustal intrusions, however, should be small enough so that the refraction - wide-angle reflection experiment does not identify individual bodies.

The picture of the present-day structure indicates that the upper crust is thinned primarily by simple shear along normal faults leading to asymmetric basins with maximum depths of almost 10 km in some cases and tilted fault blocks in the crests of which Precambrian crystalline basement rocks are sometimes exposed. The model also demonstrates that crustal thinning and anomalous mantle material are essentially restricted to and symmetrically centred beneath the surface expression of the present-day rift. This is consistent with the mantle and the deeper levels of the crust below the rift deforming by pure shear and is inconsistent with models (e.g. Bosworth 1987) requiring that the major lithospheric thinning is asymmetrically offset beneath one of the rift flanks.

Although the presence of anomalously hot mantle material giving rise to the low velocity zone under the Kenya dome in the southern part of the rift seems to dominate the scene today, this was not always so in the past history of the Kenya rift. The evidence points to the southwards migration of material from the large plume centred under Afar (northern Ethiopia) giving rise to the upwelling of anomalously hot mantle material, initial volcanism and subsequent rifting 30-25 Ma ago in the Turkana region in the northern part of the rift. However, the broad zone of extension in the north overlying thin crust suggests that passive lithospheric stretching has also played an important role in this region. As volcanism and rifting propagated southwards with time the presence of the plume centred under the Nyanza (Tanzanian) craton began to be felt. The narrow zone of extension over the culmination of the Kenya dome overlying thick crust and a mantle low velocity zone extending down to 150-200 km depth suggests that active uprising of anomalously hot mantle material with thinning of the lithosphere from below is the dominant rifting mechanism beneath the Kenya dome in the southern part of the rift.

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