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A teleseismic delay time study across the Central African Shear Zone in the Adamawa region of Cameroon, West Africa

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Summary. *P*-wave relative teleseismic residuals were measured for a network of seismological stations along a 300 km profile across the Adamawa Plateau and the Central African Shear Zone of central Cameroon, to determine the variation in crust and upper mantle velocity associated with these structures. A plot of the mean relative residuals for the stations shows a long wavelength (> 300 km) variation of amplitude 0.45 s. The slowest arrivals are located over and just to the north, of the faulted northern margin of the Adamawa Plateau. The residuals do not correlate with topography, surface geology or the previously determined crustal structure, in any simple way.

The Aki inversion technique has been used to invert the relative residuals into a 3-D model of velocity perturbations from a mean earth model. The results show the region is divided roughly into three blocks by two sub-vertical boundaries, striking ENE and traversing both the crust and upper mantle down to depths greater than 190 km. The central block, which is 2 per cent slower than the adjacent blocks, roughly corresponds to the Central African Shear Zone. The Adamawa Plateau, as an individual uplifted area, is explained by the interaction of a regional anomalous upper mantle associated with the West African Rift System, and the Central African Shear Zone, which provided a conduit for heat flow to the surface.

Key words: seismology, teleseismic delays, Aki inversion, upper mantle, West Africa

1 Introduction

This paper describes the results of a teleseismic delay time study of the lateral variation in upper mantle velocity structure beneath the Adamawa Plateau, central Cameroon (Fig. 1). The region is a post-Cretaceous uplifted plateau at the north-eastern end of the Cameroon

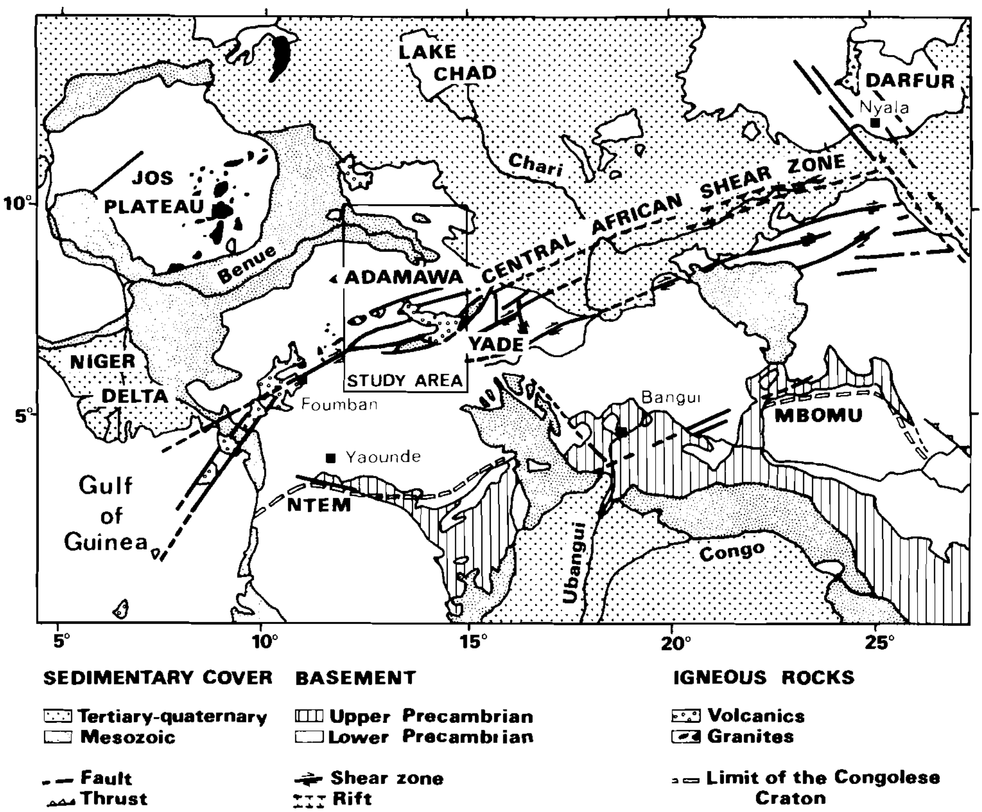

Figure 1. Regional tectonic setting, with the study area outlined.

Volcanic Line. This volcanic lineament is 1400 km long and straddles the continental margin of West Africa. Its continental portion extends approximately 700 km in a gentle curve of basaltic volcanic centres (generally 10 Myr to recent in age) from the Gulf of Guinea to central Cameroon. Morgan (1983) considered the volcanic line and the Adamawa Plateau to be related to the movement of the West African lithosphere over an upper mantle hot spot, whilst Fitton (1983), commenting on the similarity in shape between the volcanic line and the Benue Trough of Nigeria (Fig. 1), hypothesized that the volcanic line originated from an anomalous upper mantle body that was suddenly displaced from beneath the Benue Trough, as a result of a major reorganization of the plate boundaries surrounding the African continent.

The Adamawa Plateau (Fig. 2) is bounded on its northern margin by the Cretaceous Garoua rift, which is the easternmost part of the Yola rift of Nigeria, an eastern extension of the Benue Trough. Burke, Dessauvagie & Whiteman (1972) proposed that the Benue Trough was a failed arm of a Cretaceous RRR triple rift junction, with the other two arms subsequently developing into the South Atlantic and the Equatorial Fracture Zone. An alternative view is provided by Benkehil (1982) who suggests that the Trough was initiated by the continental extension of the Equatorial Fracture Zone.

A major tectonic feature of the region is the Central African Shear Zone (Fig. 1), which represents an important ENE–WSW Precambrian lineament. It can be traced geologically and geophysically for nearly 2000 km, from the Darfur region of western Sudan, across

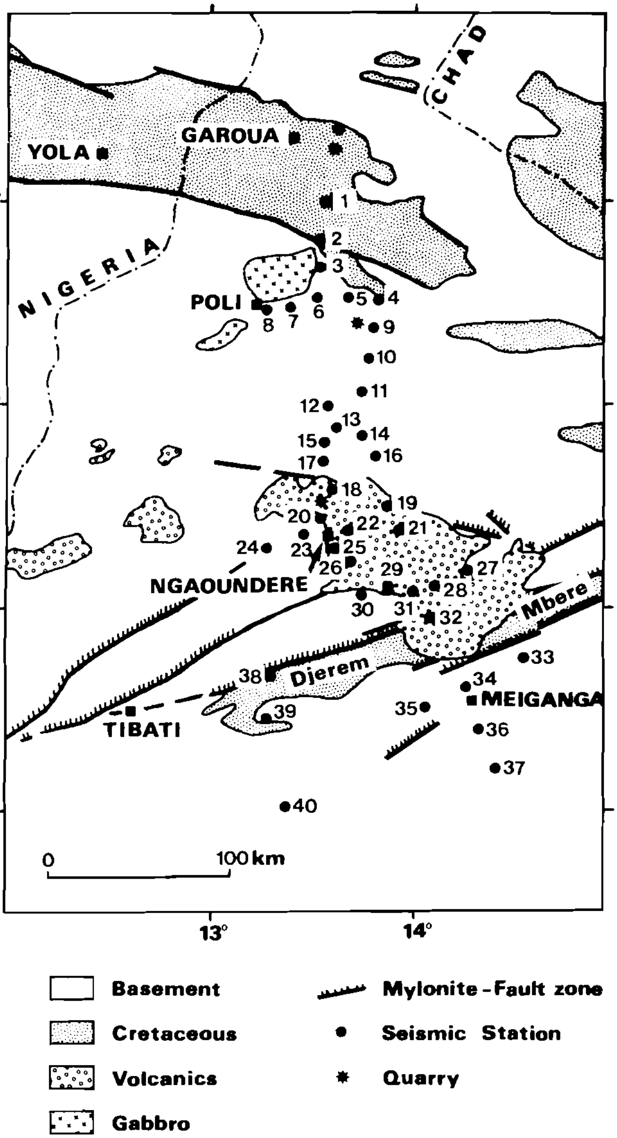

Figure 2. Location of the seismic stations on a simplified geological map of the Adamawa Plateau.

Central Africa to the Adamawa Plateau region of central Cameroon, and thence south-westwards as the exposed Foumban shear zone, before disappearing under the Tertiary to recent volcanics of south-west Cameroon (Louis 1970; Browne & Fairhead 1983; Cornacchia & Dars 1983). On pre-drift continental reconstructions this fault zone can be traced into South America as the Pernambuco fault of Brazil (De Almeida & Black 1967). The exposed part of the shear zone in Cameroon is marked by mylonites; its minimum age can be determined by the fact that it is intruded locally by Cambrian granites, and the dating of cogenetic galena at 640 Myr (Gazel 1956). Some of the faults of the shear zone have been rejuvenated several times, principally with a dextral movement, prior to, and contemporaneously with, the opening of the South Atlantic in the Cretaceous. These Mesozoic and

Tertiary movements produced elongated rifted basins in southern Chad, northern Central African Republic (Louis 1970; Brown & Fairhead 1983), and in central Cameroon as the Djerem–Mbere basin situated on the southern margin of the Adamawa Plateau (Figs 1 and 2; Le Marechal & Vincent 1972; Ngangom 1983).

The relationship between the Cameroon Volcanic Line, the Adamawa Plateau, the Central African shear zone and the Garoua rift is conjectural. Mascle (1977), following Vincent (1970), considered the Adamawa Plateau as an uplifted basement horst controlled by the faults of the Central African Shear Zone, while other workers have compared the Adamawa Plateau with other African Tertiary uplifts such as Darfur, Tibesti and Hoggar, which are thought to be accompanied by lithospheric thinning (Fairhead 1979; Bermingham, Fairhead & Stuart 1983).

Crustal seismic refraction studies (Dorbath *et al.* 1984; Stuart *et al.* 1985), undertaken concurrently with the present study, show abnormally thin crust (about 23 km) underlain by upper mantle with anomalously low velocity (7.8 km s^{-1}) beneath the Garoua rift and extending to the northern margin of the Adamawa Plateau (Figs 1 and 2), whereas beneath and to the south of the Plateau the crust has a normal thickness (about 33 km). The nature of the transition from thin to normal crust can not be determined from the seismic refraction data. The results of the crustal study are summarized as a cross-section in Fig. 4.

2 The seismic experiment and the data

The aim of the seismic experiment was to use teleseismic earthquake arrivals to map out lateral velocity variations in the lithosphere across the Central African Shear Zone in the region of the Adamawa Plateau. Hopefully, results from this study, together with the results of the seismic refraction work, would clarify the relationships between the Cameroon Volcanic Line, the Adamawa Plateau, the Central African Shear Zone and the Garoua rift, and thus provide an explanation as to their origin. To this end, a network of up to 40 vertical short-period seismic stations was deployed for five months, covering an area 80 x 300 km from the Garoua rift in the north, across the Adamawa Plateau, to the south of the Djerem–Mbere rift (Fig. 2). Due to equipment limitations not all the stations ran simultaneously. Stations 1–9 in the north (Fig. 2) were re-deployed in the south, with additional equipment, as stations 27–37, after two and a half months of recording.

The signals from each station were telemetered to one of several multichannel Geostore analogue tape recorders, whose internal time base was made absolute to within ±0.01 s by recording VLF time signals from the Omega Navigation transmitter in Liberia.

2.1 MEASUREMENTS OF *P*-WAVE ARRIVALS

Relative arrival times of the *P* phases were measured using waveform matching across the network. A reference station, with the clearest and most representative onset, was chosen to convert these relative observations into absolute arrival times. All the arrival times were read by three independent observers. Readings which disagreed by more than 0.1 s were rejected. The overall accuracy of the relative arrival times is estimated to be better than 0.05 s.

Only events with epicentral distances greater than 30° recorded by the majority of the stations have been retained. Events with epicentral distances greater than 137° have also been rejected to avoid possible misidentification among core phases. The final data set (Fig. 3) consisted of 145 spatially well distributed events, which represent only 23 per cent of the total number recorded.

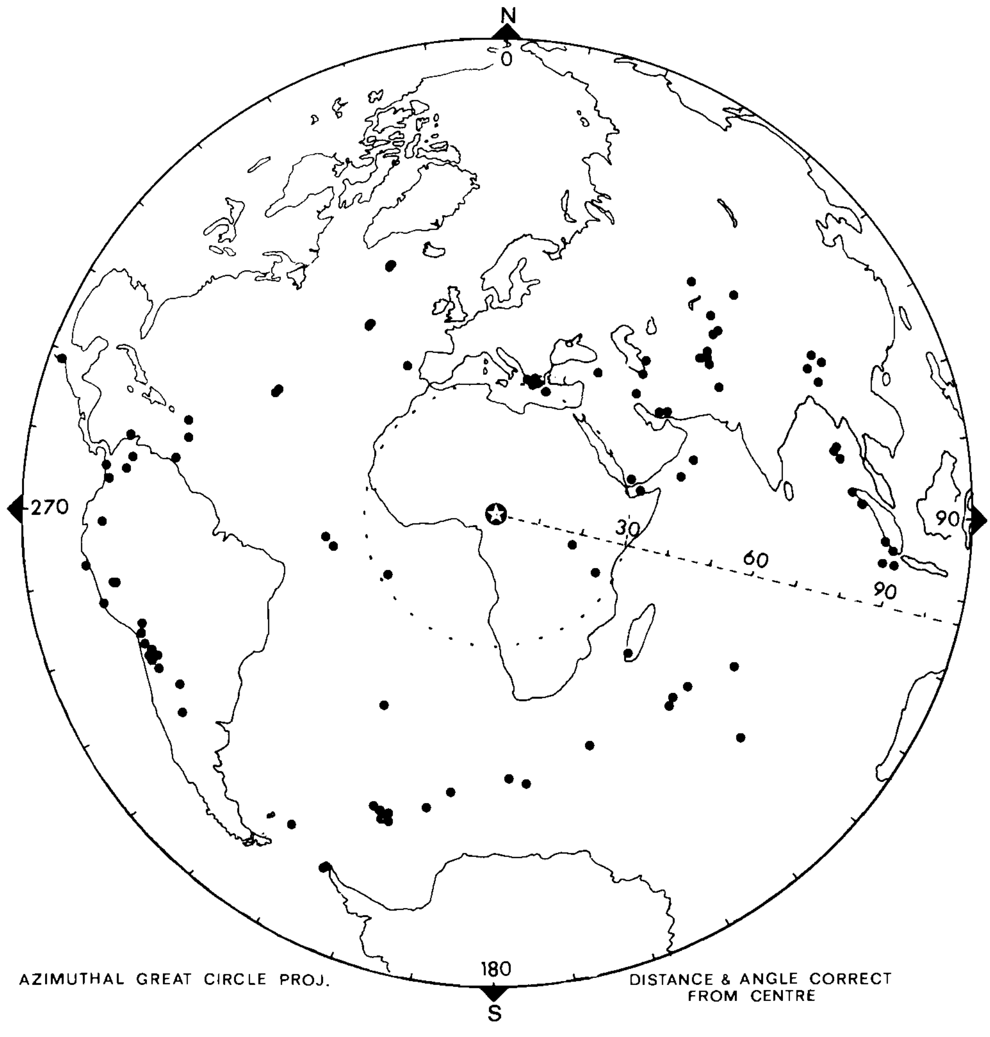

Figure 3. Epicentral distribution of earthquakes used, plotted on an azimuthal great circle projection of the globe, centred on Ngaoundere, Cameroon (Fig. 2).

2.2 RELATIVE RESIDUALS

For a particular event j recorded at a station i, the absolute traveltime residual R_{ij} is defined as

$$R_{ij} = (T_{ij} - T_{0j}) - C_{ij}$$

where T_{ij} is the observed arrival time, T_{0j} is the origin time and C_{ij} is the computed travel time for this hypocentre, using the radially symmetric Herrin 1968 traveltime tables. This latter term takes into account corrections for the Earth's ellipticity and the station elevation. Hypocentral data were obtained from the NEIS monthly listing.

The absolute traveltime residuals R_{ij} contain information on how the particular ray paths differ from a standard earth model but are not independent of source characteristics and contain errors due to hypocentral mislocation. To minimize these effects, relative residuals,

r_{ij}, are usually computed. These are calculated by subtracting the mean residual $\bar{R}_j$ for the event from each absolute residual.

$$r_{ij} = R_{ij} - \bar{R}_j,$$

where $\bar{R}_j = (\Sigma_i R_{ij}/n_j)$; n_j is the number of stations recording event j. The residuals were determined relative to the mean absolute residual, $\bar{R}_j$, calculated using stations 10–26. The reasons for choosing this subset of stations are, firstly, that they show the most uniformity in their residuals, both spatially within the network and between events (Figs 4 and 5). Stations on anomalous structures do not therefore bias the mean residual. Secondly, these stations were operational throughout the experiment, whereas stations 1–9 and 27–40 were redeployed.

3 Results

3.1 MEAN RELATIVE AND ABSOLUTE RESIDUALS

The mean relative residuals were calculated for each station and are presented on a north–south section through the network in Fig. 4, together with the topography and a summary of the crustal structure determined from the quarry blasts (Dorbath *et al.* 1984; Stuart *et al.* 1985). Fig. 4 shows that the mean relative residuals have a long wavelength variation of greater than 300 km, with the most positive residuals (the slowest arrivals) located over and just to the north of the faulted margin of the Adamawa Plateau. The residuals do not, in any simple way, correlate with the overall topography of the Plateau, the volcanics which lay principally on the Plateau, the surface geology, or the crustal structure.

For the southern half of the profile (Fig. 4), the relative residuals change more or less linearly with distance from the most negative residual −0.35 s (fastest arrival) at the southern most extremity of the network (station 37), to +0.05 s at station 18, at the centre of the profile. This change in residual positively correlates with the change in topography giving a slope of 1.2 s km^{-1}, which is similar to values determined elsewhere in Africa (1.1–1.3 s km^{-1}; Fairhead & Reeves 1977). For their position on the profile, stations 33 and 34 have residuals about 0.1 s above the regional trend (i.e. are anomalously slow) as they are affected by their proximity to the Djerem–Mbere basin (Fig. 2). Further local geological variations produce scatter in the observations.

For the northern half of the profile, the residuals decrease towards the Garoua rift, but do not reach values comparable to the southern end of the profile, despite the topography being considerably lower. However, the decrease of the residuals northwards does coincide with a region of thinned crust and the development of the large positive gravity anomaly centred over the Garoua Rift. Stations 5, 7 and 8 are anomalously fast, as was also observed on the crustal refraction records. Stations 7 and 8 are associated with the gabbroic rocks near Poli (Fig. 2) whilst station 5 is located on a large local (40 mGal) positive gravity anomaly, possibly associated with basic material of higher velocity than the surrounding rocks.

These relative residuals are referenced relative to the mean residual of stations 10–26. To compare the magnitude of the traveltime residuals over the Adamawa Plateau to those elsewhere in the world, the absolute residual of 33 earthquakes with a magnitude greater than 5.5 was computed for the slowest station 13, as 0.9 ± 0.2 s. This is a relatively large value for a region covered by Pan African rocks (Dorbath & Dorbath 1984; Poupinet 1979). However, this implies an absolute residual for the southernmost station, 37, of 0.4 s, which is normal for this elevation.

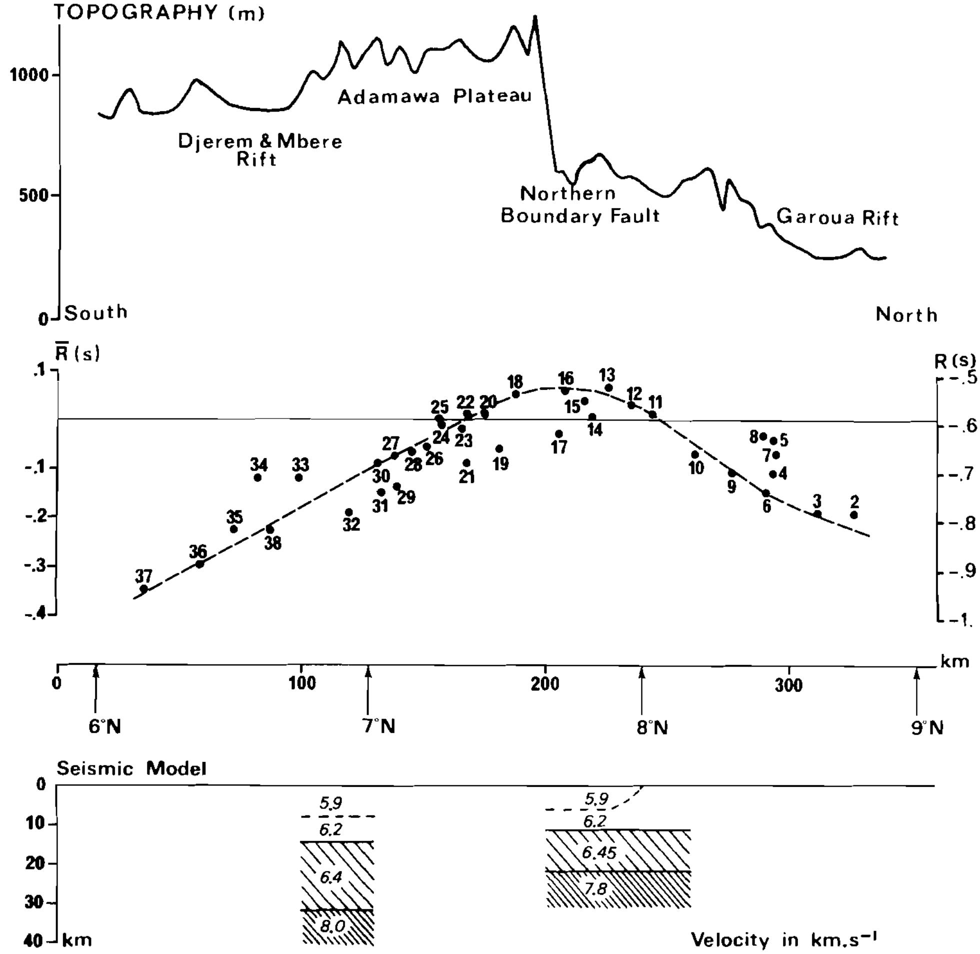

Figure 4. Mean relative residuals, $\bar{R}$, plotted on a north–south section through the network. The axis on the right of the plot shows a calibrated absolute residual, R, scale. Also shown is the topographic variation along the profile and a summary of the crustal structure determined from quarry blasts.

3.2 VARIATION OF RELATIVE RESIDUALS WITH AZIMUTH AND DISTANCE

Plots of mean relative residuals (Fig. 4) produce a rough picture of the gross velocity variations at depth. However, it is the information contained in the azimuthal and distance variation of the residuals that helps to image spatial and depth velocity perturbations from a spherically symmetric earth velocity model. Fig. 5 shows representative examples of the variation of the relative residuals along the profile from different epicentral regions from which a number of events were recorded.

The northern stations (1–9). These stations show a marked azimuthal variation, with the residuals rapidly changing from being at their most negative between N0° and N60° to being positive between N60° and N110°, before returning to negative residuals for larger azimuths. This behaviour is indicative of a lateral velocity change striking at N60°–N70° in the vicinity of stations 9 and 10, such that faster velocities occur to the north.

The central stations (10–30). These stations generally have a much reduced or absent azimuthal variation.

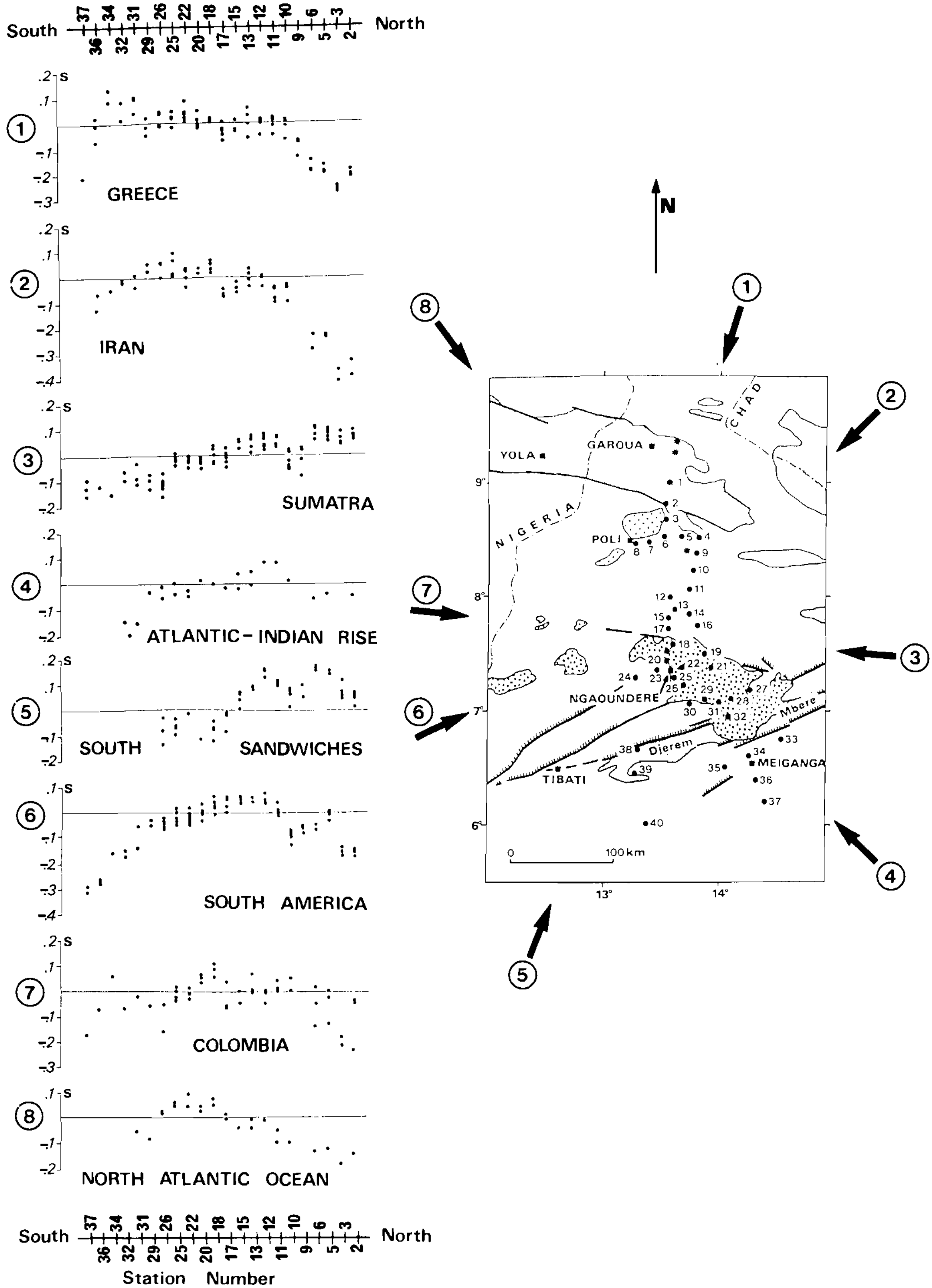

Figure 5. Examples of the variation of the relative residuals along a north–south profile from different epicentral regions.

The southern stations (31–40). These stations show the most negative residuals on southerly events, in contrast to the observations from the northern stations. This implies that the faster velocities occur to the south.

In summary, a simple qualitative model can be constructed to explain much of the gross variation in the relative residuals. This model consists of a zone of slower material (between stations 30 and 10, Fig. 5) stretching north from the Djerem–Mbere rift in the south to half-way between the northern boundary fault of the Adamawa Plateau and the Garoua rift, sandwiched by regions of faster velocity to the north and the south. The northern boundary of this central lower velocity zone occurs at about stations 9 and 10 and does not correspond with any major mapped surface geological change. However, this boundary does coincide with the northern termination of the upper crustal 5.9 km s^{-1} layer determined from the seismic refraction study (Fig. 4). Furthermore, this boundary is mentioned by Vincent (1970) as a fault dividing Pan-African granites to the south from migmatites to the north and is an along strike extension of a NE–SW trending lineament that can be traced on *Landsat* images and the gravity field in eastern Chad.

4 Inversion

The inversion technique developed by Aki, Christofferson & Husebye (1977) has been used here to invert the relative residuals into a 3-D model of velocity perturbations from a mean earth model. This method has been described and used by a number of authors (e.g. Ellsworth 1977; Taylor & Toksoz 1979; Dorbath *et al.* 1983) and involves the division of the volume under the network of seismometers into layers, which are further divided by vertical boundaries into blocks. The model is divided into four layers; the first layer is 40 km thick, underlain by three layers 50 km thick. Each block was 40 km square in plan. The block grid has been rotated to a N80° direction to correspond to the dominant grain of the surface geological structures and the trend of the regional Bouguer gravity data (Collignon 1968).

To avoid the generation of long-wavelength traveltime residual anomalies due to crustal variations, the effect of a simple velocity model for the crust and uppermost mantle down to 40 km, derived from the seismic refraction experiment, has been stripped off the observed travel-time residuals. Although the crustal model is crude, consisting of two crustal provinces (Fig. 4) with a smooth join, accounting for its effect helps to reduce any long-wavelength crustal component contaminating information from deeper in the upper mantle. In fact several inversions, with and without corrections for crustal stripping, were carried out and produced little significant change to the character of the velocity perturbations in the mantle. In other words, the well distributed data set allows good vertical resolution of the velocity perturbations between layers in the model, effectively decoupling crustal velocity effects from those of the mantle.

The solution to the inversion presented in Fig. 6 is an average of two solutions, obtained by translating the centre of the model along half the diagonal of a block. Each value plotted is therefore a mean of five values. Seventy-seven per cent of the blocks have a resolution superior to 0.75; the standard error averages 0.3 per cent in the first layer and 0.4 per cent between 90 and 140 km (Figs 7 and 8).

In the central, best-resolved, part of the model, the solution shows a two-dimensionality with a strike of about N80°, consistent with the regional trend of the geology and gravity field. Edge effects on the solution deform this general pattern. With this in mind, a schematic 2-D cross-section through the centre of the model is illustrated in Fig. 9.

The inversion shows that the qualitative model, with a central lower velocity region, surrounded by higher velocity blocks, is essentially maintained throughout the depth range

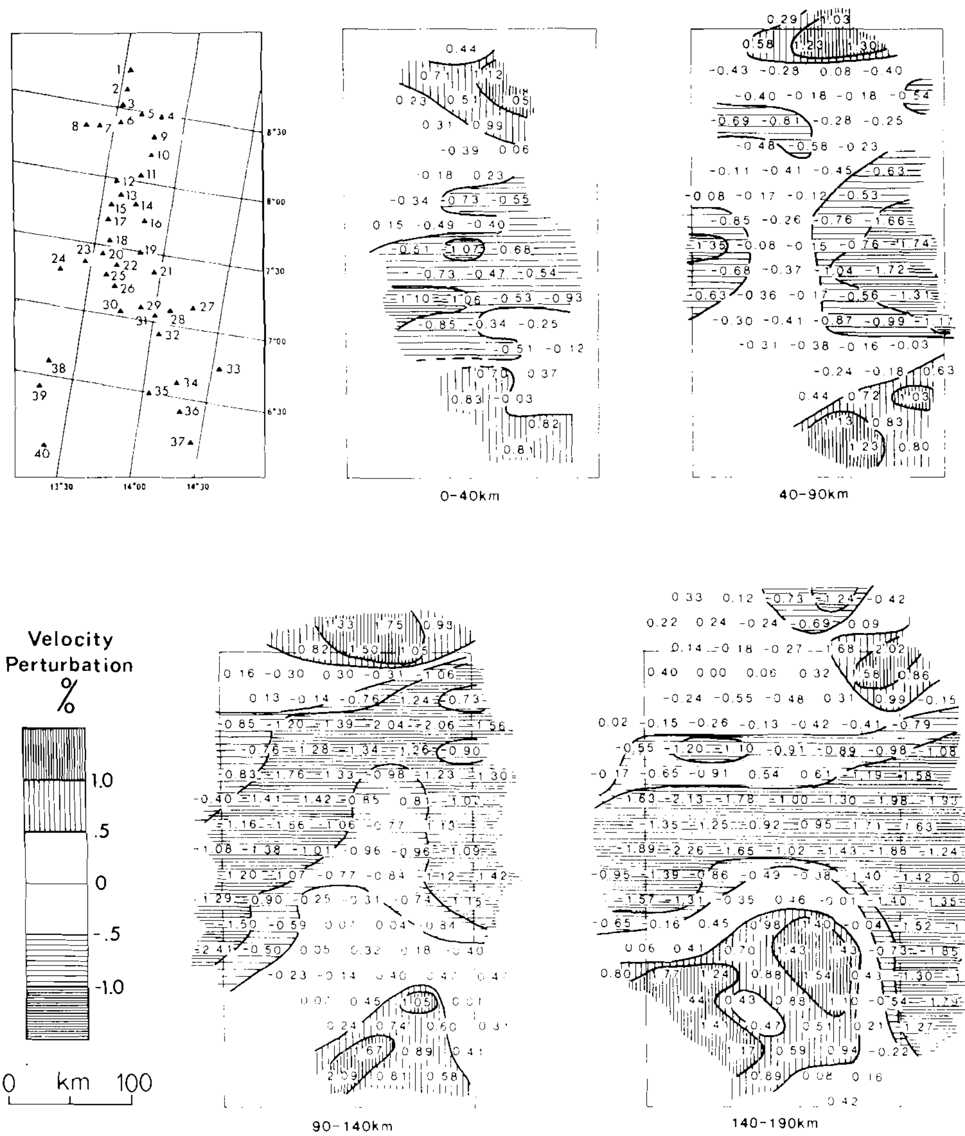

Figure 6. Result of inversion, which is an average of two solutions, obtained by translating the centre of the model along half the diagonal of a block.

of the model to depths of 190 km, but with the contrast becoming more pronounced at depth.

The boundary between the faster southern block and the slower central block is particularly well defined and is subvertical and corresponds in location with the southern edge of the Central African shear zone. The limit of the central lower velocity zone to the north is more diffuse and assumes an apparently northerly dip. The inversion suggests that the Garoua rift structure is underlain by higher-velocity upper mantle than that found beneath the Adamawa uplift, but since this area is at the edge of the model it is not fully resolved.

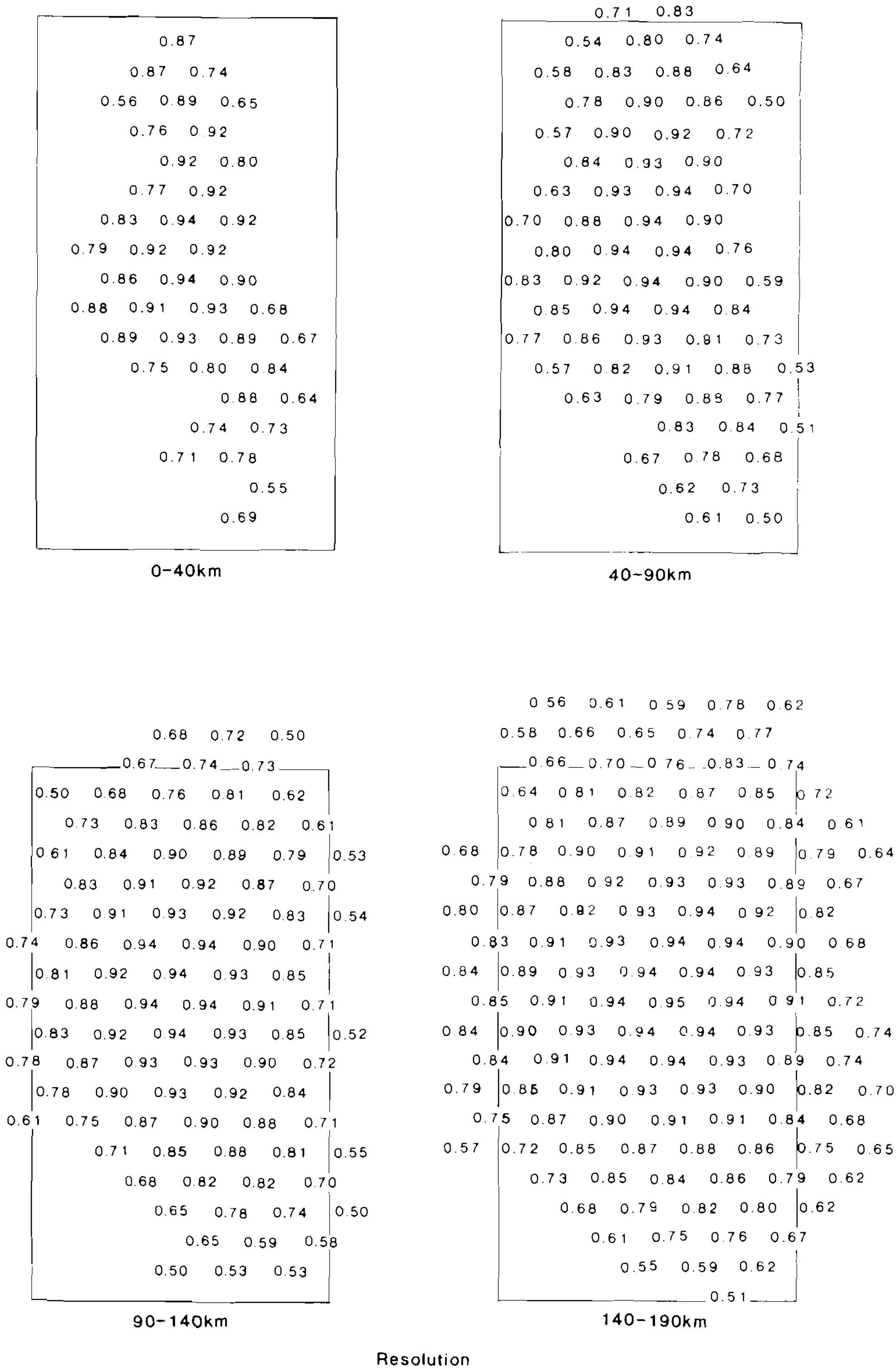

Figure 7. Diagonal elements of the resolution matrix for the 3-D inversion.

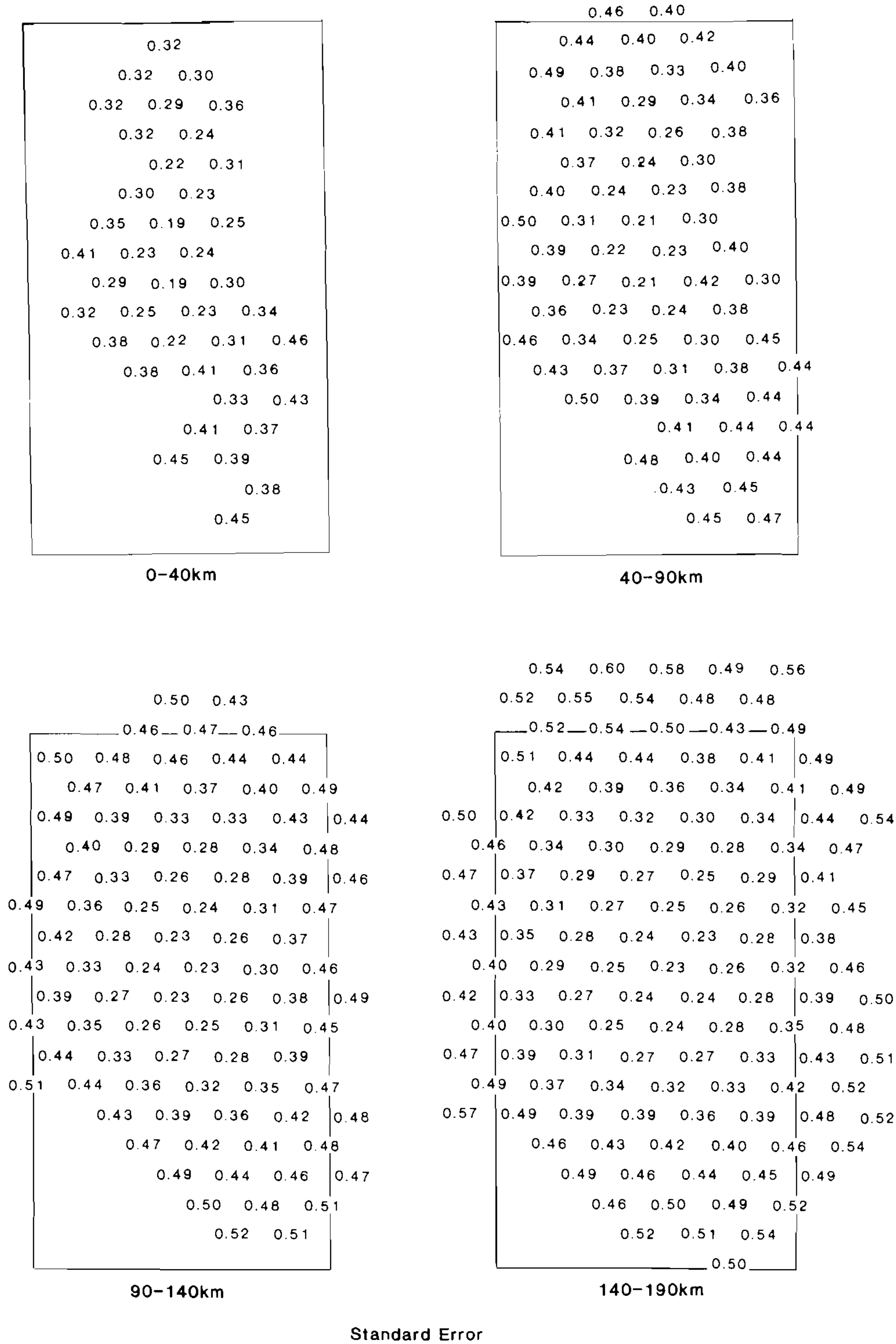

Figure 8. Standard error in model parameters as a percentage of average *P*-velocity in each layer for the 3-D inversion.

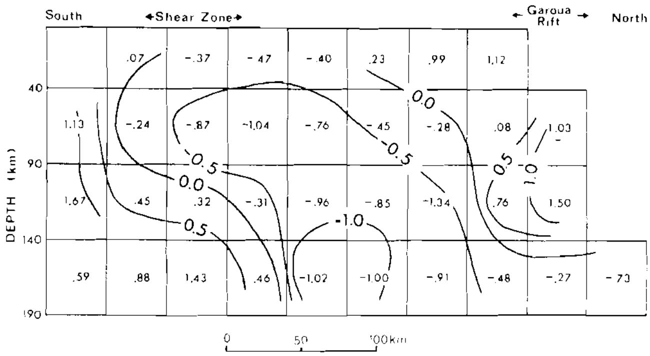

Figure 9. A schematic cross-section, trending N170°, through the centre of the inversion solution shown in Fig. 6.

5 Discussion and conclusions

The first surprising aspect of the model illustrated in Fig. 6 is the small velocity contrasts, not exceeding 2.5 per cent, for a region of marked relief and recent volcanism, despite some stations showing large azimuthal travel-time residual variations. By comparison, in a similar study in eastern Senegal (Dorbath *et al.* 1983), where all tectonic activity had ceased in the Hercynian, velocity contrasts reached 5 per cent.

Although the contrasts are weak, two subvertical discontinuities, striking ENE and traversing both the crust and upper mantle down to depths of 190 km, are delineated by this study. These discontinuities divide the region into three major blocks, the central of which is slower by about 2 per cent than its surrounds and roughly corresponds to the Central African Shear Zone. A velocity contrast of 2 per cent in the first 200 km of the Earth corresponds to an arrival time difference of about 0.5 s, which is the same order of magnitude as the maximum observed in this study. The structural trend of this lower velocity region is able to explain the azimuthal variation of station residuals on the edge of the structure.

The southern boundary is best defined by this experiment and corresponds in location with the Central African Shear Zone. The apparent northerly dip of this boundary lends support to a 'mushroom' geometry of the velocity (thermal) anomaly (see Turcotte & Emerman 1983) rather than a simple 'upwarp' of the base of the lithosphere. The northern boundary of this lower velocity region is not associated with the faulted zone, so clear on the topographic cross-section in Fig. 4, which delimits the northern edge of the Adamawa Plateau geographically. The boundary lies further north between stations 9 and 10, where changes in upper crustal structure (Fig. 4) and Precambrian geology have previously been alluded to. However, there was no indication on the refraction data of a sharp change in crustal thickness in this area. The high velocity region underlying the Cretaceous Garoua rift, located at the northern edge of the model, occurs in a region of anomalously thin crust, low P_n velocity and beneath the site of an extensional basin, subsequently subjected to shear deformation in the late Cretaceous/early Tertiary. The presence of this high velocity upper mantle may contribute to the observed positive Bouguer anomaly and suggest that annealing processes may be important in changing the mineralogy of the upper mantle over periods of approximately 60 Myr (Jarvis & McKenzie 1980) since basin formation. The sourthern part of the model shows typical Precambrian Pan-African lithosphere as implied by the absolute teleseismic residuals (Dorbath & Dorbath 1984; Poupinet 1979).

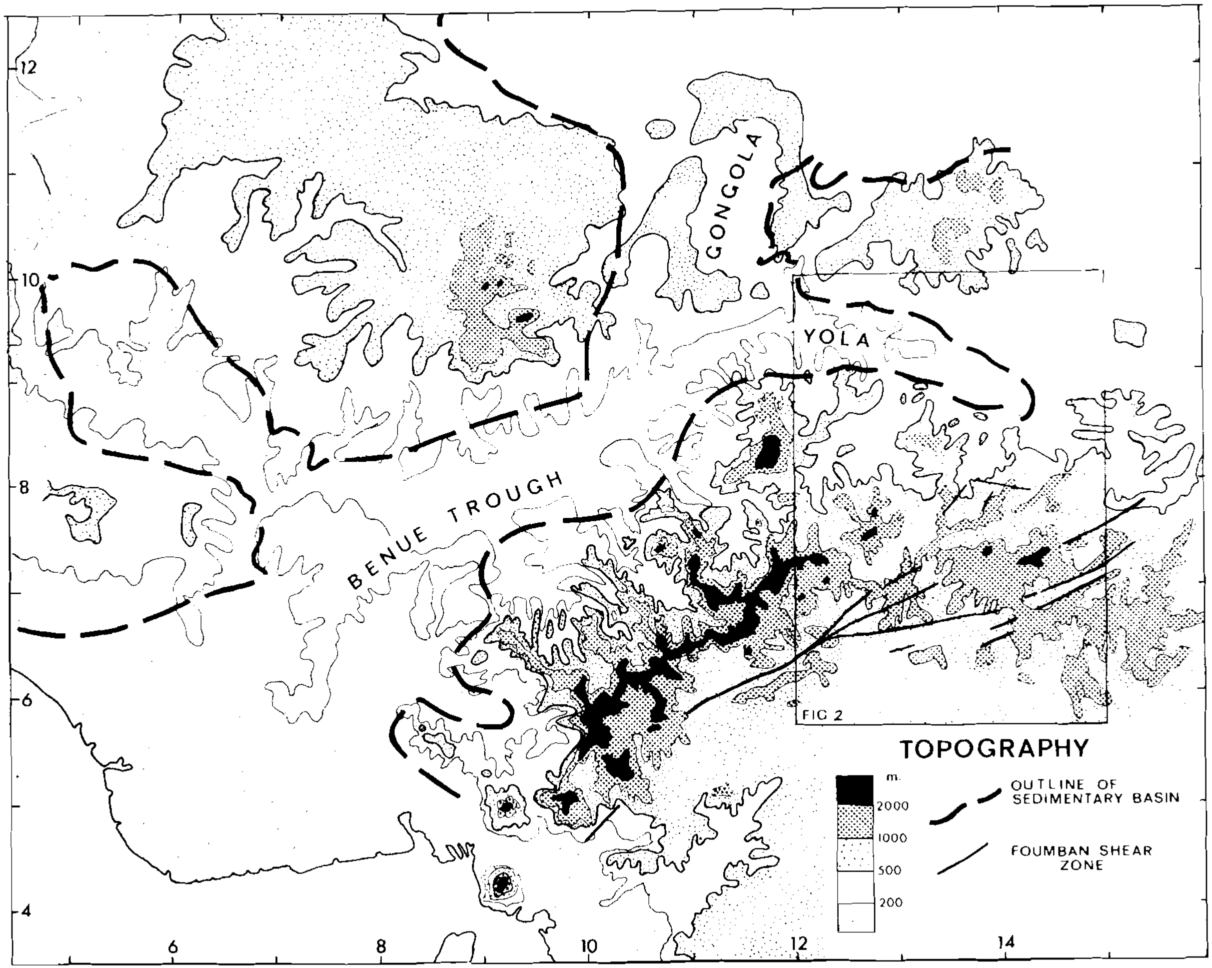

Figure 10. Regional topographic map with the study area outlined.

These findings, when placed in a regional context, provide a means of understanding the tectonic structures of West Africa. The topographic relief of West Africa (Fig. 10) shows that the Adamawa Plateau region is part of a more extensive uplifted area bordering the southern side of the Benue Trough and the Yola (Garoua) rift. Similar, but generally less elevated, topography occurs between the Yola and Gongola rifts and to the north of the Benue Trough. Since the whole region is in isostatic equilibrium for topographic features greater than 100 km in wavelength (Okereke 1984), the upper mantle velocity structure, modelled in this study, may represent the southern margin of an anomalous upper mantle region, underlying the whole of the West African Rift System. The high topography surrounding the rift system is caused by the low density, lower velocity, upper mantle, which dominates the isostatic response of the areas with normal crustal thicknesses. In areas adjacent to or within the rift system the thinned crust dominates the isostatic response, giving rise to lower topographic elevations. Spectral analysis of the gravity field of the region supports this hypothesis (Okereke 1984). The Adamawa Plateau, as an individual region, may be explained by the interaction of this regional anomalous zone with the Central African Shear Zone, which provides a conduit for heat flow to reach the surface.

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