Geophys. J. R. astr. Soc. (1985) 81, 1–12

DORBATH

A seismic refraction study of the crustal structure associated with the Adamawa Plateau and Garoua Rift, Cameroon, West Africa

G. W. Stuart and J. D. Fairhead *Department of Earth Sciences, The University, Leeds LS2 9JT*

L. Dorbath and C. Dorbath *ORSTOM, 24 Rue Bayard, 75008 Paris, and IPG, 4 place Jussieu, 75230 Paris, Cedex 05, France*

Received 1984 June 29; in original form 1984 April 6

Summary. Recordings of quarry blasts along a 300 km profile across the Adamawa Plateau at the eastern end of the Cameroon Volcanic Line permitted the determination of the crustal structure of the region. To the north of the Plateau in the area of the Garoua Rift, an eastern arm of Benue Trough, the crust is about 23 km thick and is underlain by upper mantle with a *P*-wave velocity of 7.8 km s^{-1}. The southern part of the Plateau by comparison is associated with a more normal crustal thickness of about 33 km and underlain by upper mantle with a velocity of 8.0 km s^{-1}. Between these two areas the seismological experiment was not able to delineate how the crust changes. However, if the topography and gravity field reflect crustal thickness then there is a rapid change in crustal thickness at the northern edge of the Adamawa Plateau. The study thus provides the first seismic evidence for major crustal thinning beneath the Garoua arm of the West African Rift System as well as providing evidence for an alternative model for the formation of the Cameroon Volcanic Line.

1 Introduction

The Adamawa Plateau is situated in central Cameroon, West Africa and represents a post-Cretaceous uplifted area at the north-eastern limit of the Cameroon Volcanic Line. The Cameroon Volcanic Line itself is a unique feature in that it forms a 700 km long continental segment of a much larger 1400 km long volcanic chain that straddles the African continental margin (Fig. 1). The continental segment extends from the Gulf of Guinea to central Cameroon and is characterized by a gently curving line of volcanic centres. Although the oldest intrusives give ages of 35–65 Ma, it has only been in the last 10 Myr that large quantities of basaltic rocks have erupted along the whole length of the volcanic chain. The most recent eruption was on Mount Cameroon in 1982 October/November. Dating of the oceanic and continental volcanics reveals no linear age pattern (Dunlop 1983). Petrological

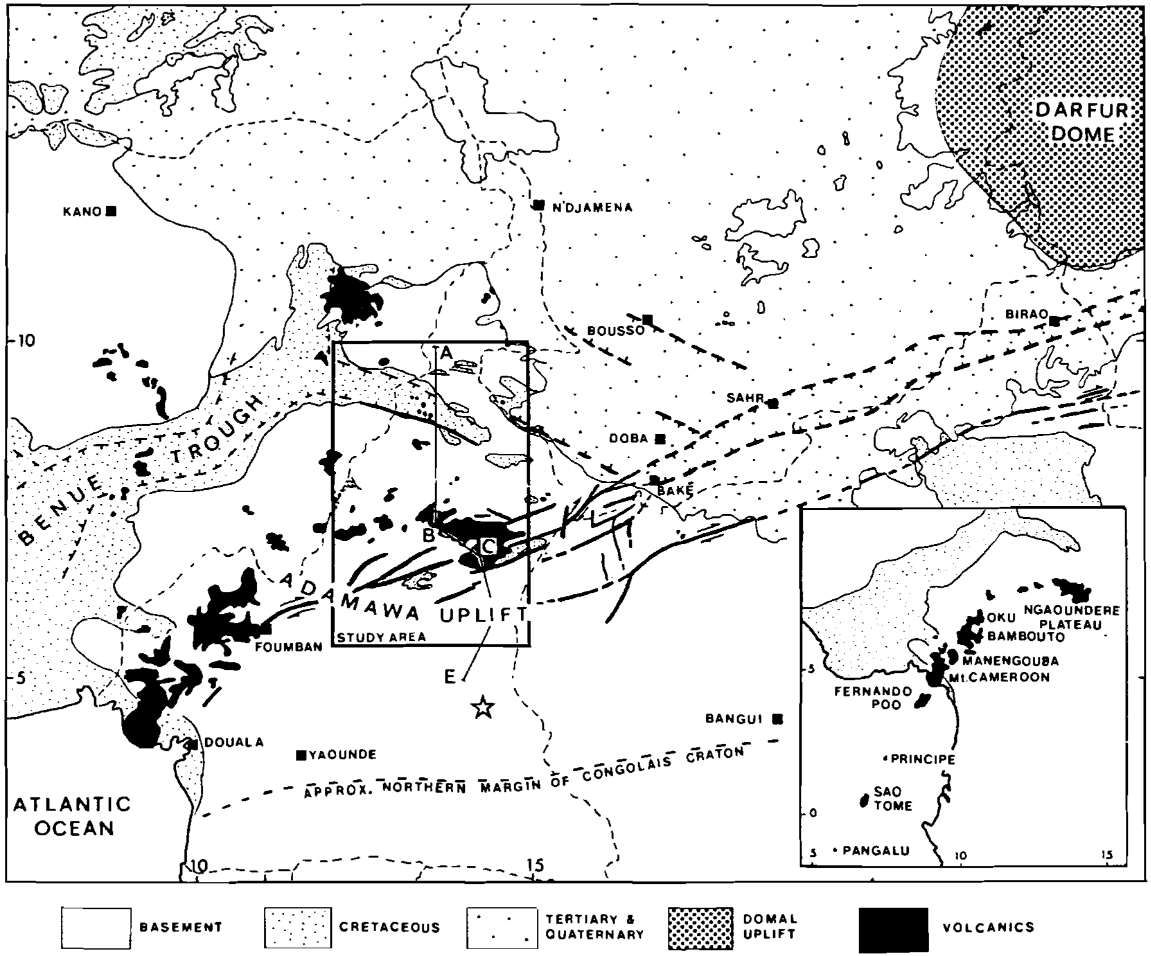


Figure 1. Regional tectonic setting. Study area is outlined. Dashed lines represent inferred position of faults under the sedimentary cover. Profile A–E is the line of the Bouguer and topographic section shown in Fig. 8. The starred position, SE of E, shows the location of the local earthquake used in Fig. 7.

studies (Fitton & Hughes 1977; Dunlop & Fitton 1979; Fitton 1983) indicate the volcanic chain is characterized by transitional to strongly alkaline volcanism, with no obvious differences between its oceanic and continental segments and is similar in affinity to many continental rift systems.

The origin of the volcanic line has been considered to be related to the movement of the lithosphere over a hot spot (Morgan 1983) or the sudden displacement at about 80–65 Ma of an upper mantle swell from beneath the Benue Trough, Nigeria, to beneath the present position of the volcanic chain, when there was a major reorganization of the plate boundaries surrounding the African continent (Fitton 1980).

The basement rocks of the Adamawa Plateau consist of Pan African (500–600 Ma) (Lasserre 1967) migmatites and granites. These are cut by the Foumban shear zone which forms a series of faults associated with major mylonite zones that can be traced from Foumban itself (Fig. 1) in an ENE direction across the Adamawa Plateau and then eastwards across central Africa to the Darfur region of western Sudan (Louis 1970; Browne & Fairhead 1983). South-west of Foumban, the shear zone is obscured by the Cameroon volcanic province. De Almeida & Black (1967) consider the shear zone to have originated in pre-Cretaceous times (probably Pan-African) since it can be traced, on pre-drift reconstructions, into the Natal region of Brazil as the Pernambuco fault. The African part of the shear zone has been reactivated in the Cretaceous during the initial phases of the opening of the South Atlantic, resulting in a series of subsiding grabens along its length, e.g. the elongate sedimentary basins formed between Baké and Birao (Fig. 1). In the Adamawa region, the Djerem–Mbere basin, north of Meiganga, is another example of one of these basins (Fig. 2) (Le Marechal & Vincent 1971; Ngangom 1983) and is sampled by the seismic profile.

The Garoua Rift forms the northern boundary structure to the Adamawa Plateau. This Cretaceous rift is a side rift of the Benue Trough. Burke, Dessauvagie & Whiteman (1972) consider the Benue Trough to be a failed arm of a Cretaceous RRR triple junction; the other two rifted arms have subsequently developed into the South Atlantic Ocean and the Gulf of Guinea.

This paper describes the results of a crustal refraction study to determine the lateral variation of crustal structure south, from the Garoua Rift, across the Plateau, to just south of the Djerem-Mbere rift at Meiganga. This study was aimed at answering a number of questions. First, whether the Garoua Rift is associated with thin crust as inferred by the stretching model of McKenzie (1978) and if so, the magnitude and lateral extent of the thinning; second, whether the Cameroon Volcanic Line and the Adamawa Plateau were underlain by anomalous crust which would give a clue to their origin and finally the effect of the Foumban shear zone on crustal structure.

The location of the seismic profile was governed by the presence of working quarries, whose blasts provided convenient sources (Fig. 2) to construct seismic refraction lines. The station locations were a compromise between providing sufficient coverage between the quarries to determine crustal structure and the requirements of a teleseismic delay time experiment which was carried out at the same time. The results of this latter study will be reported elsewhere.

2 The seismic experiment

The experiment ran for a five month period (1982 November–1983 March). It was a joint venture by the University of Leeds, Great Britain; Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), France and Institute de Recherches Géologiques et Minières (IRGM) Cameroon. Due to equipment limitations, not all the stations ran simul-

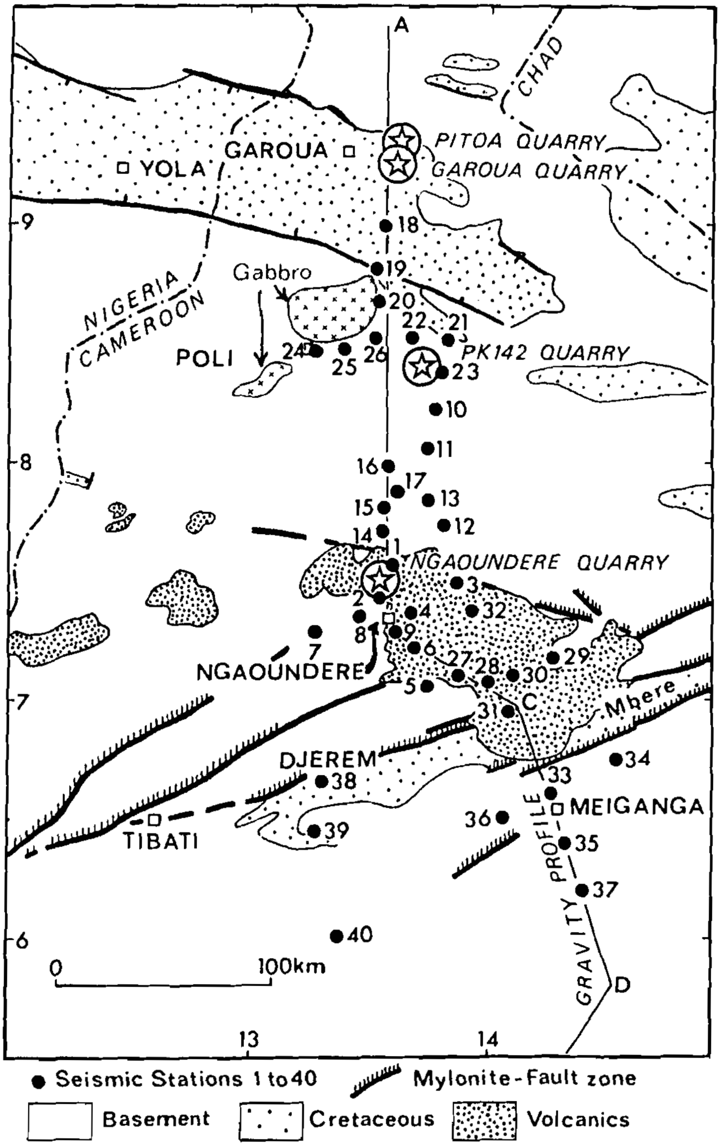


Figure 2. Location of the seismic stations relative to the quarries and main geological features. Starred positions show the location of blasts used as sources.

taneously; stations 18–26 in the north (Fig. 2) were redeployed with additional equipment in the south as stations 27–37, after 2½ months recording. Each station consisted of a vertical short-period Willmore Mk III seismometer. The station distribution along the 300 km profile (Fig. 2) was provisionally set at 15 km intervals but was ultimately controlled by the existing roads, tracks and telemetry requirements. The signals from each station were telemetered to one of several multichannel Geostore analogue tape recorders, whose internal time base was made absolute by recording VLF time signals from the Omega Navigation transmitter in Liberia.

There were four quarries in operation along the profile (Fig. 2). The two northernmost quarries, Pitoa and Garoua, are situated along the northern margin of the Garoua Rift, PK142 quarry is in Precambrian supra-crustal rocks south of the Rift but north of the Plateau and Ngaoundere quarry is on Tertiary volcanics at the centre of the 300 km profile. All quarries were accurately located, but only the Garoua, PK142 and Ngaoundere blasts were accurately timed. The origin times of events from the Pitoa Quarry were estimated using data from the nearby Garoua Quarry as control. Charge sizes varied up to 3000 kg at Ngaoundere, but were often less than this elsewhere. These quarries provide a 200 km reversed seismic line from Garoua to Ngaoundere. Unfortunately there were no working quarries to the SE of Ngaoundere to reverse the southern half of the profile across the Foumban shear zone. However, a local earthquake (shown as a star in Fig. 1) was recorded, with its epicentre ~ 200 km to the south of the profile and provided some P_n data from the south.

3 The data

During the five months of the experiment, over 30 blasts were recorded from these four quarries. However, due to blast size and signal quality only a subset of these were worth further analysis; three from the northern quarries, two from PK142 and five from Ngaoundere in the south. Examples of these events are displayed as reduced travel-time seismograms in Figs 3–6, using a reduction velocity of 6.0 km s^{-1}. For clarity not all station records have been displayed although *all* stations were used in the analysis.

3.1 GAROUA TO NGAOUNDERE PROFILE

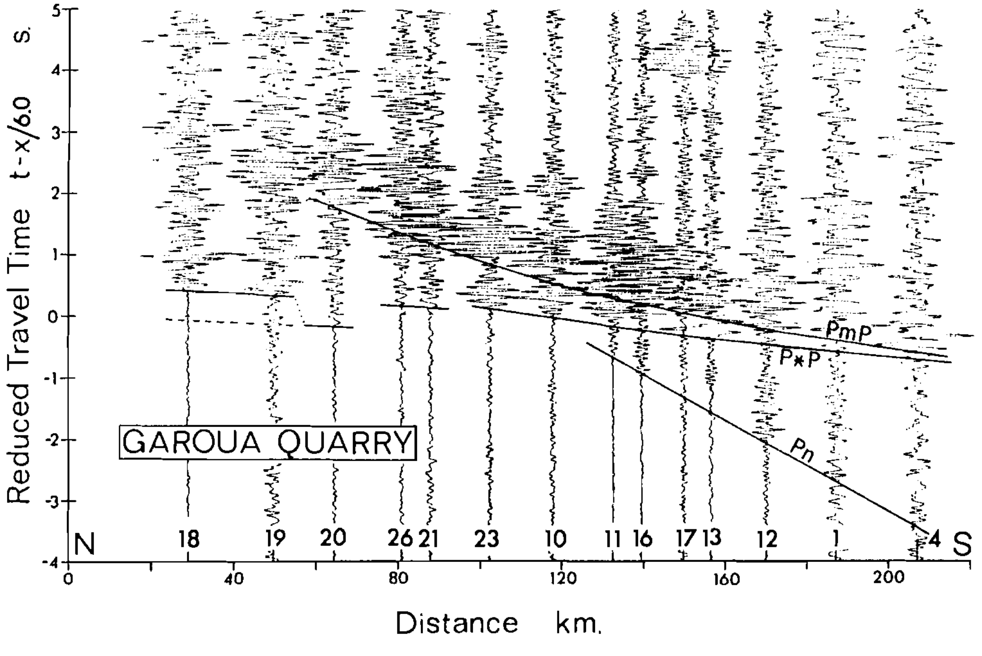
3.1.1 Direct waves and upper crustal phases

The first arrivals from the two northern quarries vary somewhat in character (Fig. 3). Pitoa, the northernmost quarry is situated on basement and as such has injected more energy into the crystalline rocks. The first arrivals at the closest stations (18 and 19), which lie on Cretaceous sediments within the Garoua Rift, have apparent velocities of 6.2 km s^{-1} and represent refracted waves from the Precambrian basement beneath. The observed reduced travel time of this phase of around 0.5 s implies sediment thicknesses underlying the stations of around 3 km. (Elf Serepca kindly provided average velocities from local seismic reflection work for the sediments which varied from 2.5 km s^{-1} at the surface to 4.0 km s^{-1} at the base of the sediments.) The same phase with a similar apparent velocity is recorded between stations 26 and 21 (Fig. 3), which lie to the south of the Garoua Rift.

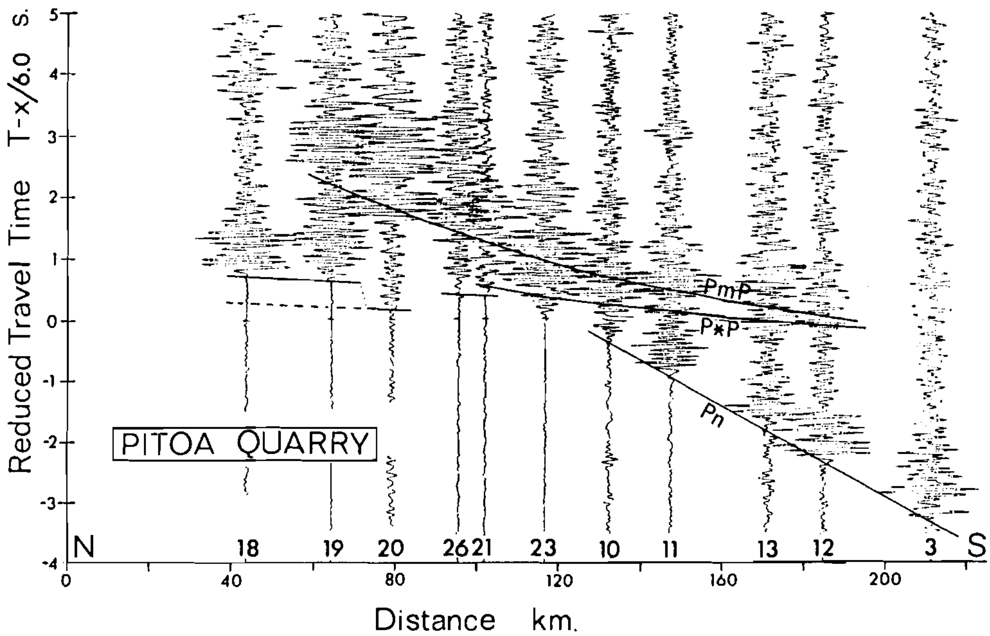
The northern travelling arrivals from PK142 quarry (Fig. 4) indicate a near surface layer with *P*-wave velocities of 6.0 km s^{-1}, overlying a 6.2 km s^{-1} layer as shown for the northern quarries. The position and the shallow depth of this 6.2 km s^{-1} layer coincide with a positive Bouguer anomaly (Fig. 8) which flanks the Garoua Rift and crops out as a gabbroic body around Poli to the north of stations 24–26.

Moving southwards the first arrivals within 35 km from PK142 shooting southwards (Fig. 4) show velocities of 5.9 km s^{-1} while at greater distances apparent velocities of 6.2 km s^{-1} are picked up again. Northerly first arrivals from the Ngaoundere blasts (Fig. 5) similarly show first arrivals with velocities between 5.4 and 5.9 km s^{-1} being overtaken at around 50 km with a phase of velocity 6.2 km s^{-1}. These data imply a layer of 3–4 km thick, which must thin northwards towards PK142, overlying the 6.2 km s^{-1} layer.

From 100 km up to the end of the profile the northern quarries show a phase with an apparent velocity of 6.3 km s^{-1} (*P*P* on Fig. 3). From the nature of the amplitude variation,



(a)



(b)

Figure 3. Reduced travel-time plots for seismograms recorded south from the Garoua (a) and Pitoa (b) quarries. The numbers against each trace refer to the station numbers shown in Fig. 2. For clarity not all station records have been used. Dashed line between stations 18 and 19 represents phase corrected for Garoua Rift sediments.

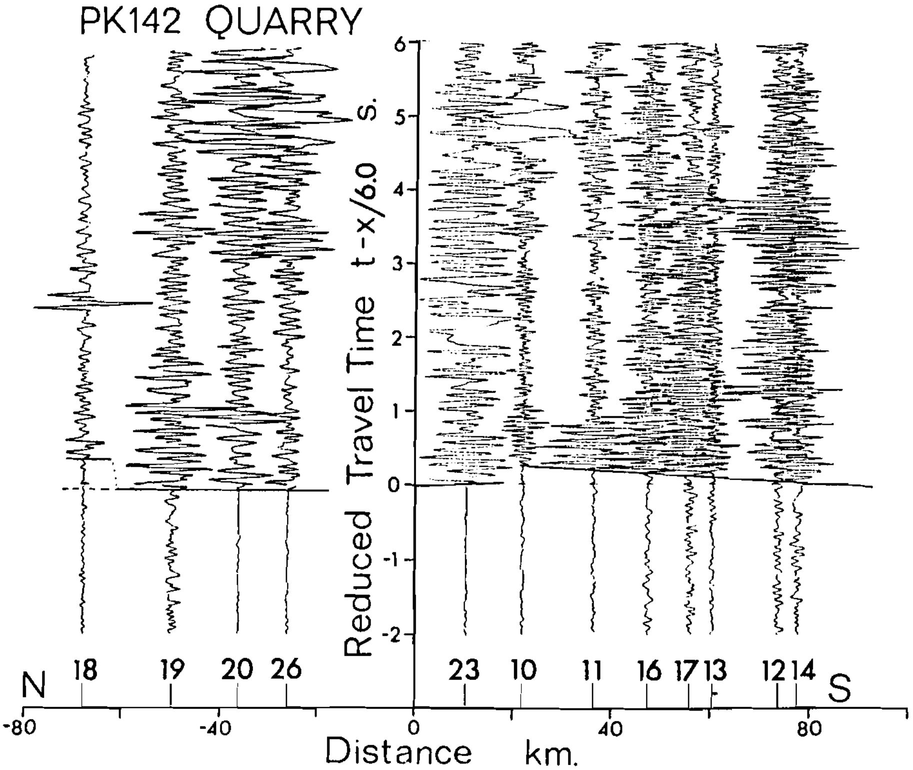


Figure 4. Reduced travel-time plots for the seismograms recorded north and south of the PK142 quarry.

particularly at 100 km, this phase is interpreted as a reflection from an intra-crustal discontinuity at a depth of about 14.5 km with an average velocity down to the interface of 6.2 km s^{-1}. On the reverse shot (Fig. 5) the *P*P* phase can be identified and also gives a mean velocity of 6.2 km s^{-1}. Although this result implies there is little dip on the interface its depth is estimated to be 12.5 km from these northerly arrivals.

3.1.2 Refracted and reflected Moho phases

The blasts from the northern quarries display Moho arrivals both as reflections and refractions (Fig. 3). The Moho P_n refraction is clearly seen from its critical distance and becomes a first arrival from 125 km distance with an apparent velocity of 7.8 km s^{-1}. Strong Moho reflections, *PmP* arrivals, can also be identified and have been utilized to estimate a crustal thickness of 23 km and an average crustal velocity of 6.3 km s^{-1}, assuming a horizontal interface, in the region just to the south of the Garoua Rift. These data are corroborated by those from the Pitoa quarry, 15 km to the north of the Garoua quarry (Fig. 3). An attempt was made to use the individual *PmP* reflection times and an assumed velocity model of the crust in the region to map any topography on the Moho immediately south of the Rift. However, within the error of the assumptions and the observations there is no measurable dip on the Moho in this region.

This profile was reversed by the blast at Ngaoundere, which did not show the *PmP* arrivals clearly (Fig. 5). However, P_n refractions can only be seen on the furthest station from these

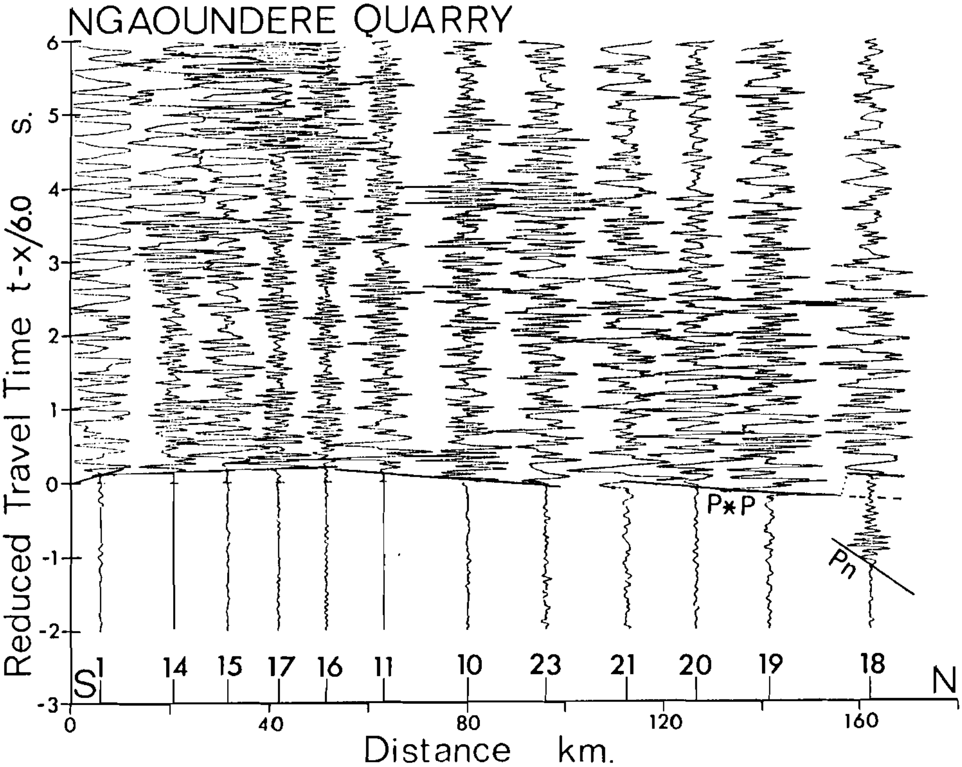


Figure 5. Reduced travel-time plots for the seismograms recorded north of the Ngaoundere quarry.

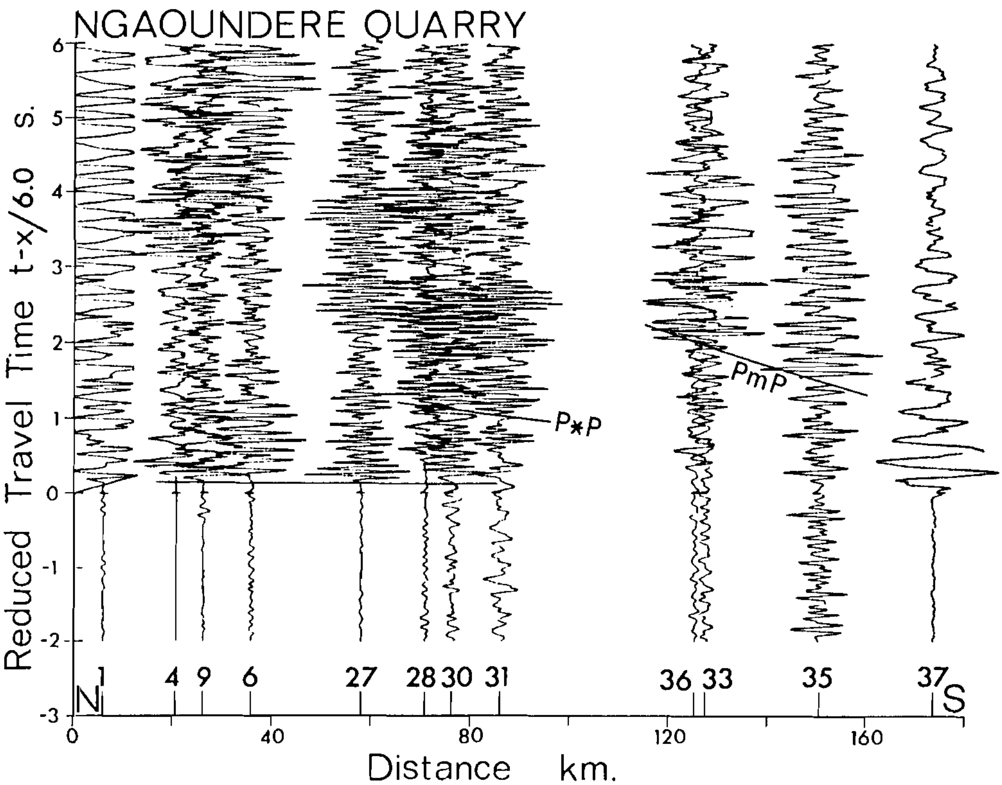


Figure 6. Reduced travel-time plots for seismograms recorded south of the Ngaoundere quarry.

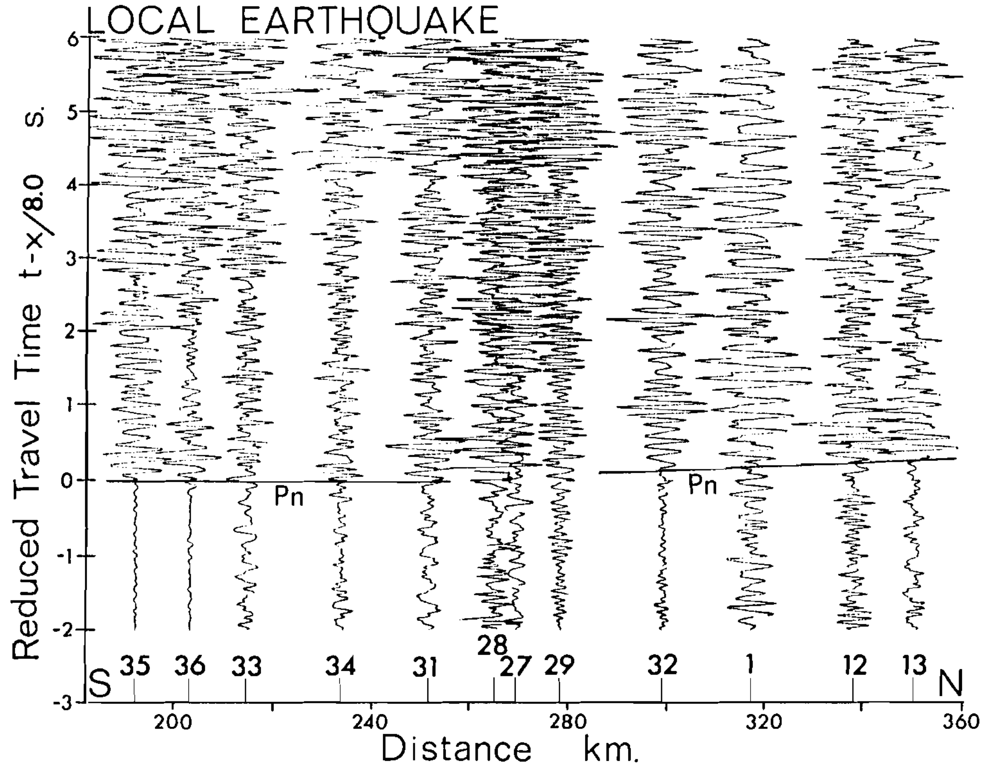


Figure 7. Reduced travel-time plots using a reduction velocity of 8.0 km s^{-1} for seismograms from the local earthquake located 200 km south of Meiganga (see Fig. 1).

southern blasts. It is difficult to use these refracted arrivals meaningfully due to the uncertainty of the error in the estimate of the relative time corrections required to account for the lateral variation of the sediment cover across the Rift. Nevertheless the arrivals give a cross-over distance which is about 15 km greater than that from the northern quarries. Since we have good control over the crustal thickness in the Garoua region from the *PmP* arrivals in both directions, this greater cross-over distance must imply a thicker crust below the Ngaoundere quarry itself.

To summarize these results, between the Garoua Rift and Ngaoundere the crust can be divided into an upper crust 13–14 km thick with a mean velocity of 6.2 km s^{-1} overlying a lower crust about 10 km thick with a mean velocity of 6.45 km s^{-1}. The *P*-wave velocity below the crust is about 7.8 km s^{-1} and there is evidence for the crust increasing in thickness as one moves from the Garoua Plain on to the Adamawa Plateau.

3.2 NGAOUNDERE TO MEIGANGA PROFILE

The data from the Ngaoundere quarry to the SE along the length of the volcanics and across the crest of the Adamawa Plateau, tells a different story (Fig. 6). Up to distances of 60 km the first arrivals are scattered, reflecting the complex surface geology. However, with regionalization one can categorize the arrivals into two groups. (1) An upper formation is present and probably represents the effects of the volcanics and the underlying sediments. This formation is several hundreds of metres thick and has a velocity of 5.4 km s^{-1} and overlies a 6.0 km s^{-1} layer similar to that seen north of Ngaoundere. (2) Below this layer velocities of 6.2 km s^{-1} are once again observed. Beyond 70 km the intra-crustal reflection *P*P is seen. Since this profile is unreversed the depth to this interface is calculated by simply* assuming an average velocity of 6.2 km s^{-1}. The reflector is calculated to increase in depth southwards from 14 to 15 km.

At distances greater than 120 km a later reflector is observed which is interpreted as *PmP*. Assuming a horizontal Moho, its depth is found to be 32.5 km with an average velocity of 6.3 km s^{-1}. P_n is not observed as a first arrival even at the furthest station which lay ~ 170 km from the source. The cross-over distance for the model derived from the *PmP* reflection is approximately 170 km.

The P_n data from the local earthquake (Fig. 7) with an epicentre distance ~ 200 km south of the profile clearly shows a P_n velocity of 8.0 km s^{-1} on the stations to the south of the Djerem–Mbere basin. However, the arrivals are far from clear to the north, probably due to disruption of the signal at Moho depth across the Foumban shear zone. Tentative evidence is given in Fig. 7 for a disruption in the P_n arrivals around stations 27, 28 and 29 where a major fault is mapped to cross the profile. This is also where the first arrivals from the Ngaoundere quarry become difficult to correlate in Fig. 6.

4 Discussions and conclusions

One can briefly review the results of this study of crustal structure (Fig. 8) by saying that between the Garoua Rift and the northern margin of the Adamawa Plateau, one finds an abnormally thin crust (~ 23 km) underlain by upper mantle with anomalously low velocity. To the south of the Plateau the crust has a normal thickness (~ 33 km). Between these two regions it is difficult from the data presented here to see how these contrasting crusts join. However, there is an indication from the cross-over distance of the northern P_n arrivals from the Ngaoundere quarry that the crust thickens rapidly on to the Plateau at its northern margin, i.e. in the region of the fault scarp located between stations 14 and 1 (Fig. 2) and marked by F in Fig. 8. This fault has a parallel trend to the Garoua Rift and approximately marks the northern boundary of the volcanics in the region. Such a model is consistent with the poor quality of the P_n signals recorded from the northern quarries south of station 14; the rapid change in topography (Fig. 8) along the fault at F which possibly reflects isostatic compensation at the Moho and the steep gravity gradient centred over the northern margin of the Plateau.

From this study it has become apparent that the Adamawa Plateau has a normal crustal thickness unaffected to any major extent by the presence of the volcanic line. The similarity in shape between the Cameroon Volcanic Line and the Benue Trough–Garoua Rift system (Fig. 1) has previously been commented on by Fitton (1980) who explained this correspondence by suggesting that the volcanic line was formed by an upper mantle swell displaced from beneath the Benue Trough at 80–65 Ma. However, the results of this seismic refraction experiment show the volcanic line lies at the margin of the thinned crust associated with the Garoua Rift. Thus the rapid transition in crustal structure may have played a major role in controlling the spatial distribution of the Cameroon volcanic centres. The rise of the magma is considered to have utilized the presence of this crustal flexure during the post-Cretaceous uplift of the Adamawa Plateau and during the reactivation of the Foumban shear zone since many of the volcanics have erupted along the extension of the numerous faults in the region.

Surprisingly this study has shown little to no change in crustal structure across the Djerem–Mbere basin. It must be assumed that any such feature is localized and has been inadequately sampled by the station spacing. However, disruption of P_n arrivals around stations 27, 28 and 29 (Fig. 7) implies that the faults associated with the Foumban shear zone may be of crustal extent.

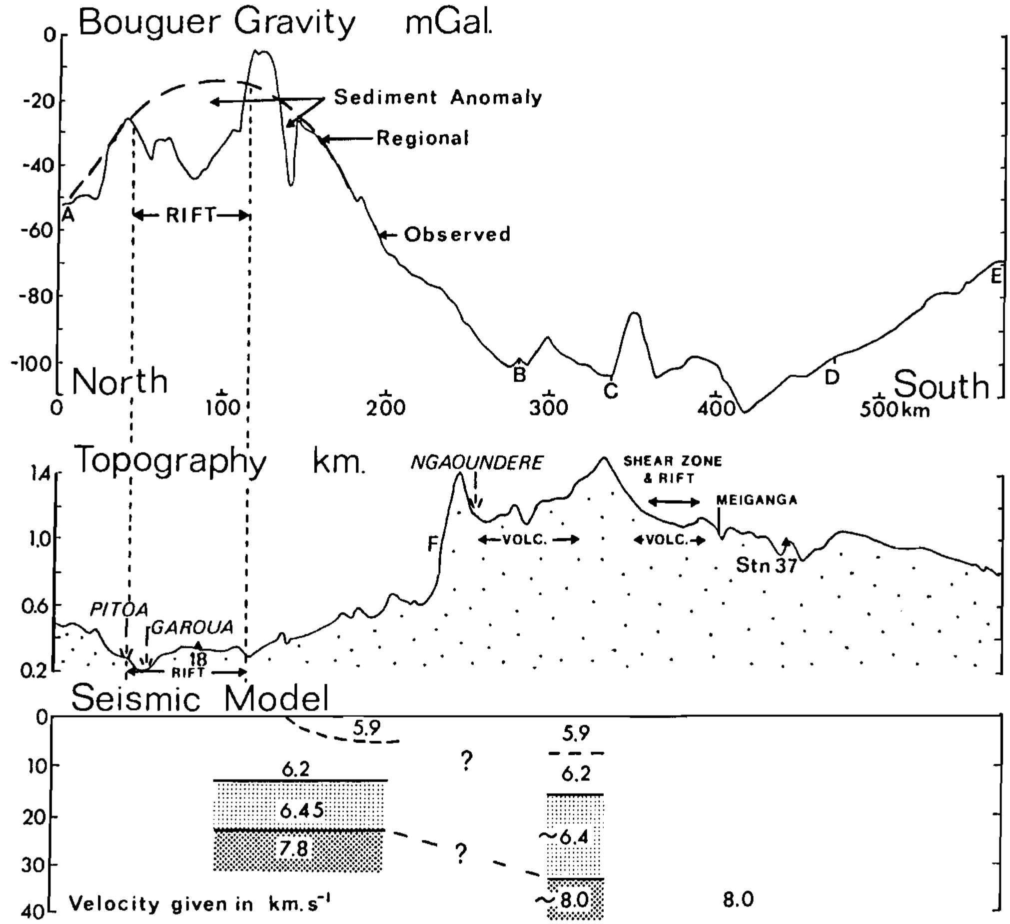


Figure 8. Seismic model of the crust together with topography and Bouguer gravity along profile A–E (Figs 1 and 2).

Finally the major result of this study is the identification of thinned crust beneath, and to the south of, the Garoua Rift. The lateral extent of this thinned crust appears to be reflected by both the low topography and the positive Bouguer gravity anomaly (Collignon 1968; Fig. 8). Interpretations of similar positive gravity anomalies over the Benue Trough (see Ajakaiye 1981) have resulted in a range of crustal thinning estimates depending on the density contrast used. This study indicates that the upper limit of 10–12 km of 'mantle uplift' determined using a density contrast of $0.17\,g\,cm^{-3}$ between the crust and mantle is consistent with our seismological results. If this thinned crust is the result of crustal stretching (after McKenzie 1978) then the West African Rift System has undergone considerably more crustal extension than previously thought.

Acknowledgments

We wish to thank NERC, Great Britain; ORSTOM, France and IRGM Cameroon for providing funds and logistic aid to make this project possible. Pat Bermingham helped immensely during data acquisition; Roger Clark during data processing.

References

Ajakaiye, D. E., 1981. Geophysical investigations of the Benue Trough – Review, *Earth Evol. Sci.*, **2**, 110–125.

Browne, S. E. & Fairhead, J. D., 1983. Gravity study of the Central African Rift System: A model of continental disruption 1: the Ngaoundere and Abu Gabra Rifts. *Tectonophys.*, 94, 187–203.

Burke, K. C., Dessauvagie, T. F. J. & Whiteman, A. J., 1972. Geological history of the Benue Valley and adjacent areas, in *African Geology, Ibadan 1970*, pp. 187–205, eds Dessauvagie, T. F. J. & Whiteman, A. J., University of Ibadan.

Collignon, F., 1968. *Gravimetrie de Reconnaissance, Cameroun*, ORSTOM, Paris.

De Almeida, F. F. & Black, R., 1967. Comparison structurale entre le nord-est du Bresil et l'Ouest africain, *Symp. Continental Drift*, Montivideo.

Dunlop, H. M., 1983. Strontium isotope geochemistry and potassium-argon studies on volcanic rocks from the Cameroon Line, West Africa, *PhD thesis*, University of Edinburgh.

Dunlop, H. M. & Fitton, J. G., 1979. A K-Ar and Sr isotopic study of the volcanic rocks of the island of Principe, West Africa – evidence for mantle heterogeneity beneath the Gulf of Guinea, *Contr. Miner. Petrol.*, 71, 125–131.

Fitton, J. G., 1980. The Benue Trough and the Cameroon Line – a migrating rift system in West Africa, *Earth planet. Sci. Lett.*, 51, 132–138.

Fitton, J. G., 1983. Active versus passive continental rifting: evidence from the West African Rift System, *Tectonophys.*, 94, 473–481.

Fitton, J. G. & Hughes, D. J., 1977. Petrochemistry of the volcanic rocks of the island of Principe, Gulf of Guinea, *Contr. Miner. Petrol.*, 64, 257–272.

Lasserre, M., 1967. Donnees geochronologiques nouvelles acquis au ler janvier 1967 par la methode au strontium appliquee aux formations crystallines et cristallophylliennes du Cameroon, *Ann. Fac. Sci. Clermont Ferrand. 36. Geol. Min. Fasc. 16.*

Le Marechal, A. & Vincent, P., 1971. Le Fosse cretace du Sud-Adamoua (Cameroun), *Cah. ORSTOM, Ser Geol.*, 3, 60–67.

Louis, P., 1970. Contribution geophysique a la connaissance geologique du bassin du Lac Tchad, *Mem. 42*, ORSTOM, Paris.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins, *Earth planet. Sci. Lett.*, 40, 25–32.

Morgan, W. J., 1983. Hotspot tracks and the early rifting of the Atlantic, *Tectonophys.*, 94, 123–139.

Ngangom, E., 1983. Etude tectonique du fosse Cretace de la Mbere et du Djerem, Sud-Adamoua, Cameroun, *Bull. Cent. Rech. Expl.-Prod. Elf-Aquitaine*, 7, 339–347.