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Geophysical and geological evidence for the Benue–Chad Basin Cretaceous rift valley system and its tectonic implications

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Abstract—Various geological and geophysical studies of the Chad Basin and Benue trough are reviewed. We critically examine the geodynamic models previously proposed for the region and finally present our own model. The main points of this model are as follows: a Precambrian origin for the major anomaly of Haraz, the Benue trough interpreted as a failed arm of the triple junction created during the opening of the Atlantic, the interpretation of the Bake–Birao trough as an extension of the Ngaundere–Mbere system rejuvenated in the Cretaceous; and a phase of extension in the East Niger contemporaneous with the Benue closing.

INTRODUCTION

THIS PAPER is a review and summary of work previously presented or published independently by the authors (Cratchley and Jones 1965, Louis 1970, Ajakaiye and Burke 1973, Ajakaiye 1981). These accounts have been variously referred to in papers by several authors as evidence in support of their hypotheses regarding the mechanisms which might have been associated with the breakaway of South America from Africa during the Cretaceous (Burke *et al.* 1971, Artsybashev and Kogbe 1974, Burke and Dewey 1974, Olade 1975, Wright 1975, 1976, Burke 1976, Offodile 1976, etc.). The purpose of the present paper is to give a summary of the important features in our interpretation of the geological work of others as well as our own geophysical studies as they relate to the rift system of the Benue trough and Chad Basin.

It appears to us that not only have some of the published results been over-simplified in some of the proposed hypotheses but also in some cases, the proposed hypotheses contain significant omissions or errors since the most recent results have not been used. This applies particularly to interpretations of the development of rift valleys through the Chad Basin in support of triple junction development. This account aims to set on record the important geological/geophysical features of the region and to assess these as evidence for or against the recent hypotheses proposed by others.

OUTLINE OF THE WORK

During the period from 1959 to 1979, a regional gravity network was established over the Chad Basin and Benue Valley in West and Central Africa. Over the major part of the basin (Republics of Cameroun, Niger and Tchad) gravity surveys were carried out by the Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM), Paris. In the southwestern part of the basin (Nigeria) and the Benue trough, gravity and magnetic surveys were carried out mainly by the Overseas Geological Surveys (OGS), London and the Geological Survey of Nigeria, and by various individuals. Altogether at least 34,000 gravity stations were established over an area of 180 degree squares. In addition 13 seismic refraction lines were placed over significant gravity anomalies in NE Nigeria and 300 long line electrical resistivity soundings were made across the major troughs in the basin.

The results of these surveys have been reported in detail by Cratchley (1960), Cratchley and Jones (1965), Louis (1970), Myada (1979), Osazuwa (1978), Adighije (1979), Ajayi (1979), Ajakaiye (1981) etc. This paper summarizes the main results and interpretations in terms of the major structural features of the Chad Basin and Benue trough, and discusses their possible significance in relation to the opening of the South Atlantic Ocean and hypotheses proposed in the literature (Grant 1971, Burke and Dewey 1974, Burke 1976, Wright 1976).

GENERAL GEOLOGY

The Chad Basin occupies a vast area at an altitude of between 200 and 500 m above sea level in central Africa, over most of which the Quaternary Chad formations masks older rocks (Fig. 1). Of particular importance to

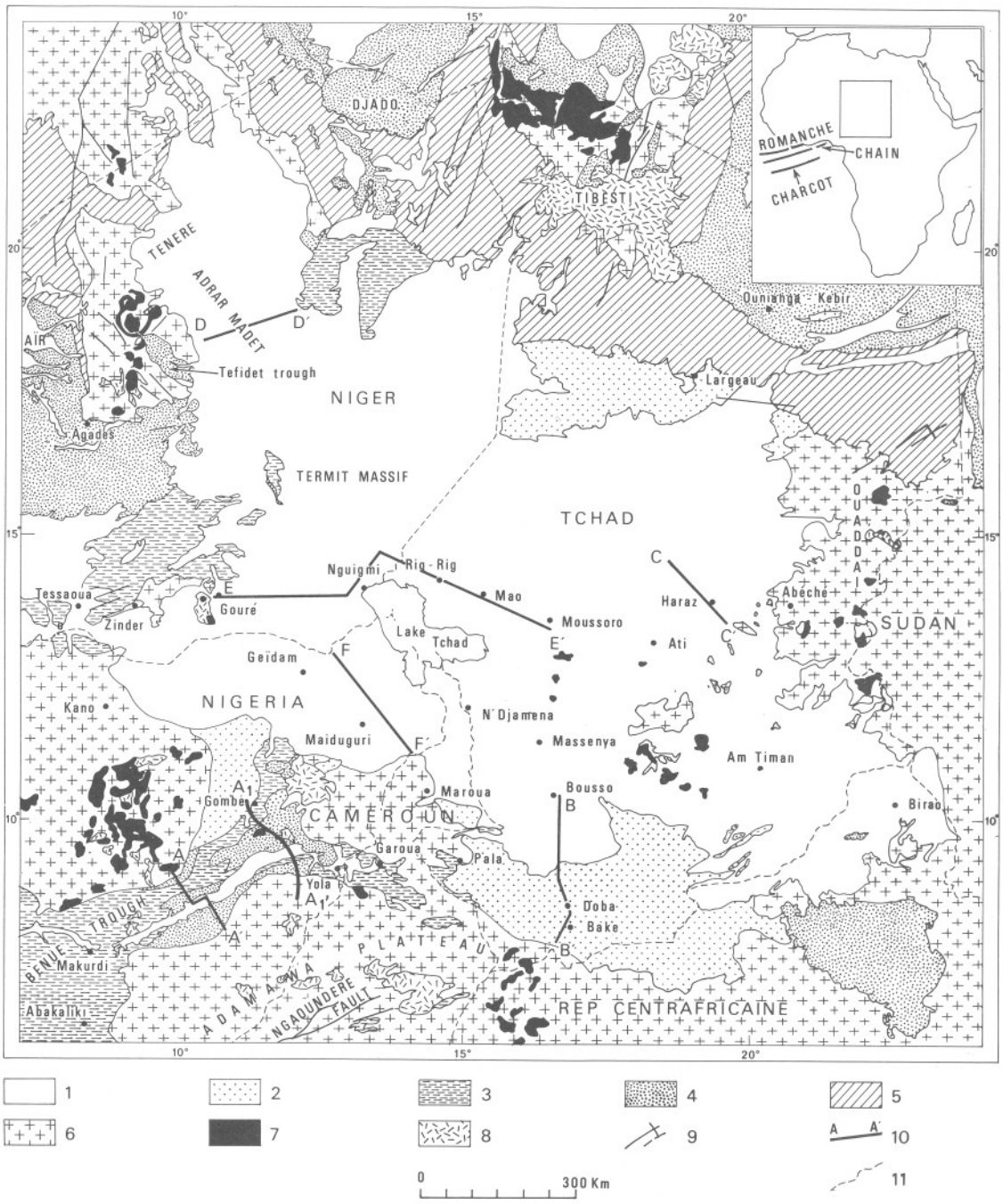

Fig. 1. General geology of the Chad Basin: (1) Quaternary: Chad formation Lacustrine clays, (2) Tertiary: "continental terminal" sandstones, (3) Mesozoic: Middle and Upper Cretaceous mainly marine shales, (4) Mesozoic: "continental intercalaire" sandstones and grits, (5) Paleozoic: sediments, (6) Precambrian: crystalline basement complex granites and gneisses, (7) post-tectonic intrusive rocks including younger granites, (8) basic and acidic volcanic rocks, (9) fault, (10) line of gravity profile and (11) international boundary.

the present study are the Cretaceous rocks and the crystalline basement rocks of, presumably, Palaeozoic or Precambrian age.

The Chad formation comprises lacustrine clays with occasional sands dipping at low angles towards the lowest point in the NE corner of the basin (south of Largeau). The sands form artesian aquifers, particularly in NE Nigeria to the south and west of Lake Chad, and much of the present-day knowledge about this formation and the rocks immediately underlying it derive from geological survey and borehole exploration for artesian water. In eastern Tchad the basin is shallow with Quaternary sediments directly overlying the crystalline basement which frequently outcrops in this area (Fig. 1). Elsewhere, as we shall demonstrate, considerable thicknesses of Cretaceous rocks occur beneath the Chad formation, either proved as in the Maiduguri borehole, or, inferred from geophysical evidence outcrops. Such areas are shown in Fig. 1, the Benue trough in the SW being particularly important and containing folded Cretaceous strata ranging in age from Albian to Maestrichtian (Carter *et al.* 1963, Cratchley and Jones 1965, Offodile 1976, etc.). Exploratory boreholes for oil have also proved great thicknesses of Cretaceous strata,

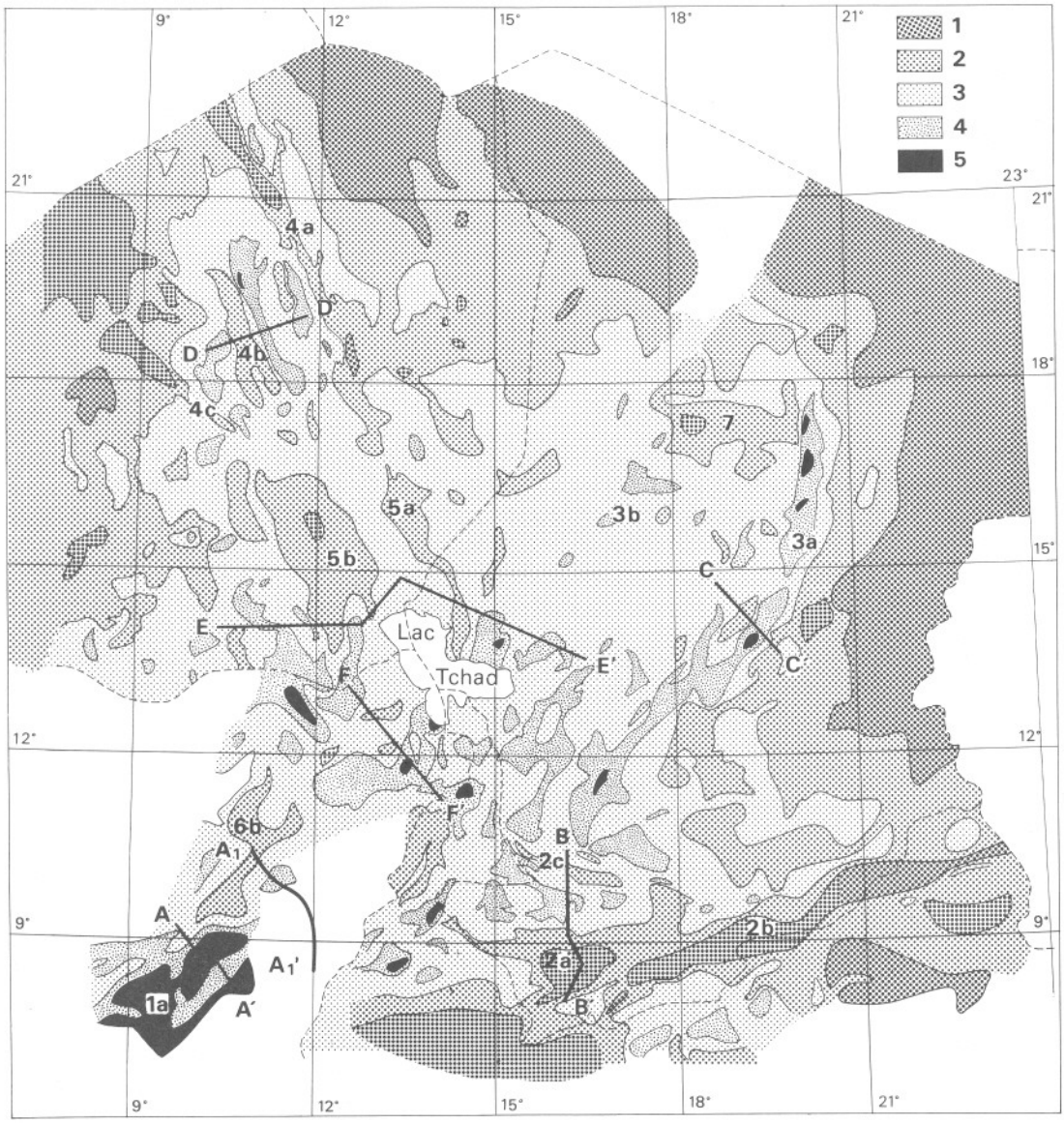

Fig. 2. Schematic outline of the Bouguer anomaly of the Chad Basin. A–A′: line of gravity profile. 1a,b,c: Benue trough; 2a: Doba trough; 2b: Bake–Birao trough; 2c: Bousso trough; 3a: Haraz positive anomaly; 4a: Ténéré rift; 4b: Ténéré rift; 4c: Téfidet rift; 5a: Rig-Rig anomaly; 5b: Termit anomaly; 6a: Maiduguri trough; 6b: Gombe trough; 7: Largeau Basin. 1: <−70 mgals; 2: − 70 to −50 mgals; 3: −50 to −30 mgals; 4: −30 to −10 mgals; 5: >−10 mgals.

particularly in Southern Tchad (Doba trough) and to the north and south of Lake Chad.

Both marine and continental facies of Cretaceous age are found in boreholes located in Maiduguri and are particularly significant in any discussion concerning rifting and possible marine invasion via the Benue trough into the Chad Basin itself. Continental facies represented by massive sandstone formations (e.g. the Bima sandstone of Cenomonian age) are known to occur both in the Benue trough and in the Niger basin to the west of the present study area.

Palaeozoic formations exist in the region but their presence or absence beneath the Chad formation is unknown.

Where exposed around the edges of the basin and as inliers within it, the crystalline basement comprises mainly granite and gneiss with smaller areas of mica schist. Basalts and minor basic and acidic intrusions, particularly of Tertiary age, are common, especially in Tibesti and Cameroun, and to a lesser degree in Air. Minor intrusions and basalts of probable mid-Cretaceous are known in the Benue trough. The Jurassic "Younger Granite" intrusions of the Jos Plateau and Air are also noteworthy.

Several major tectonic directions are seen in the basement, particularly NW–SE fractures in the Air and NNE–SSW fractures in Tibesti.

GRAVITY ANOMALIES

The major features of the Bouguer gravity field are shown in Fig. 2 based primarily on Cratchley (1960), Cratchley and Jones (1965) and Louis (1970).

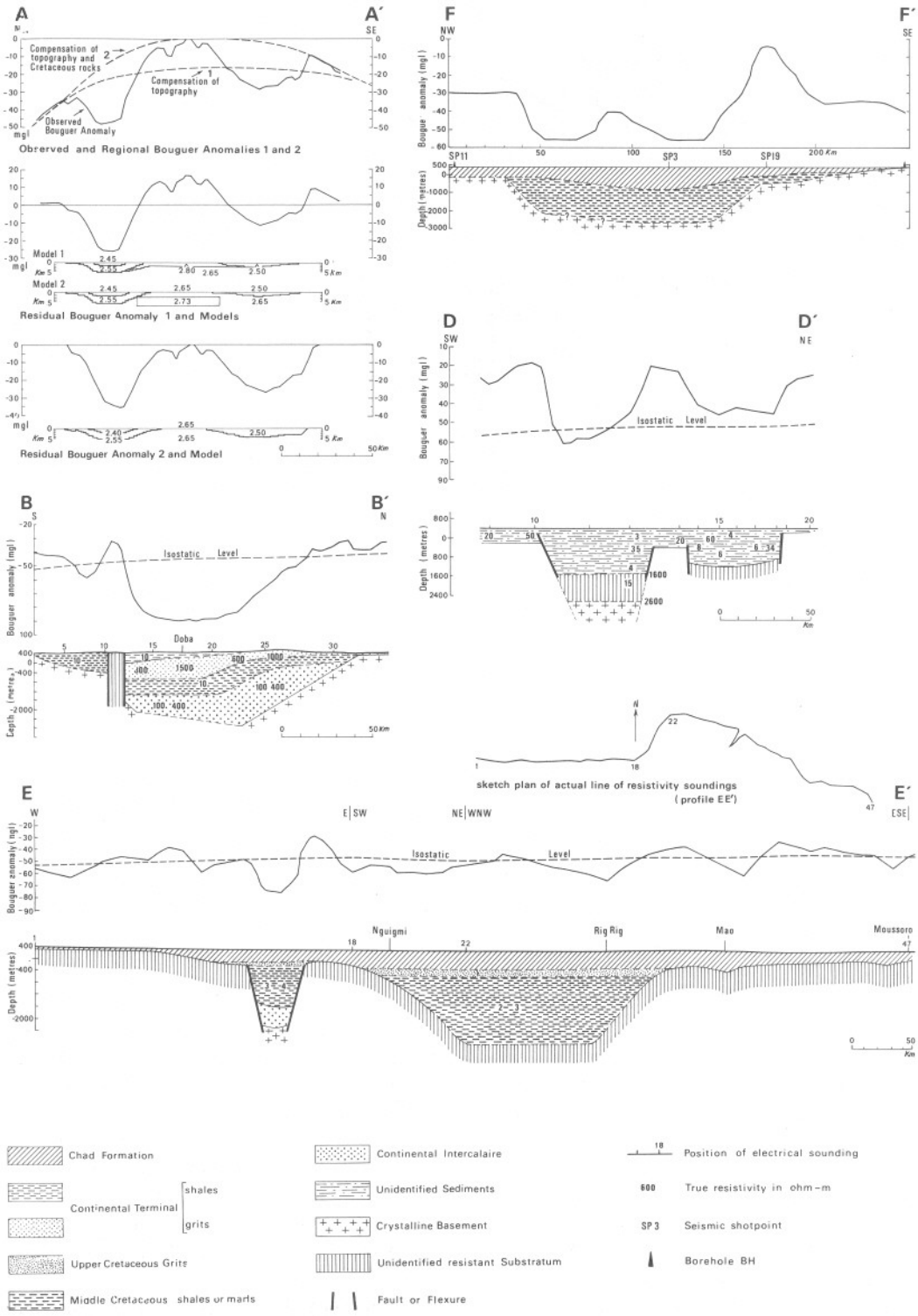

Fig. 3. Interpreted sections along Bouguer profiles.

Anomaly 1—*The Benue trough*

The Benue trough has been considered by many authors in discussion on the origin of this feature (King 1950, Carter *et al.* 1963, Burke *et al.* 1971, Grant 1971, etc.). The present authors consider that the account given by Cratchley and Jones (1965) in interpreting the geological and gravitational evidence stands as a reasonable explanation of the origin and subsequent development of the Benue trough.

The characteristic gravity profile across the Cretaceous trough (profile AA′ Fig. 2) shows a marked central positive anomaly flanked over the length of the Middle Benue by two negative anomalies. Interpretation of this profile is by a two-dimensional model in which the regional Bouguer anomaly requires crustal thinning beneath the centre of the trough in excess of that necessary for isostatic compensation of topography alone. In general, the axial positive regional anomaly observed across the trough could be attributed to a thinning of the

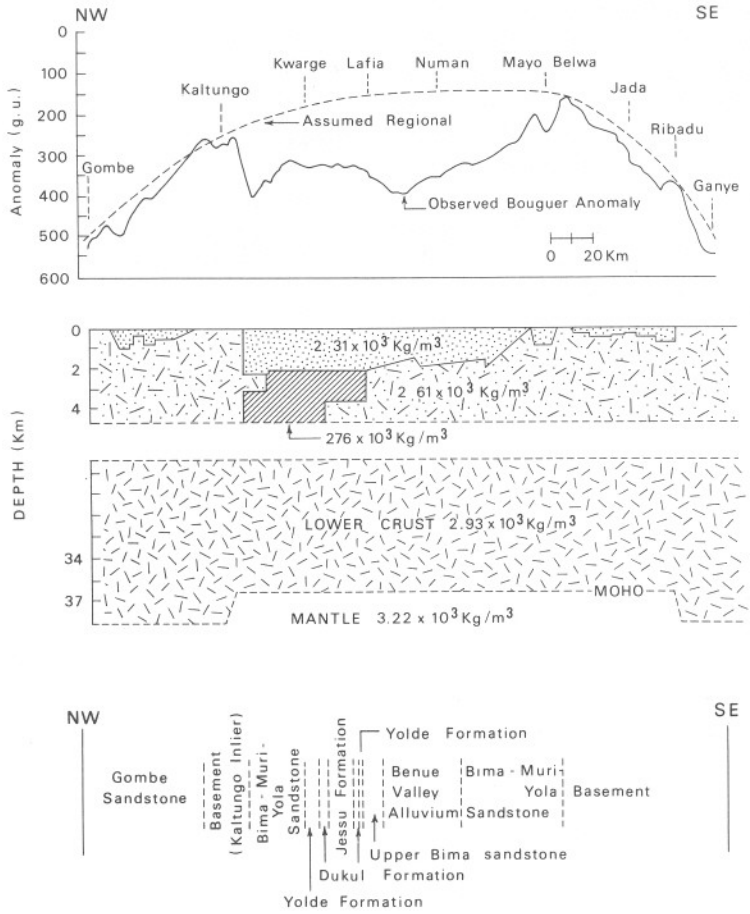

Fig. 4. Crustal structure along profile A1-A′1 [adapted from Osazuwa *et al.* (1981), assuming an irregular basement surface and basic intrusion into the basement along weak zones].

crust of the order of 2–8 km assuming a density contract of 0.37×10^3 kg/m^3 between the lower crust and the mantle in this area. The three attenuation models of Fig. 3 show varying amounts of excess mass near surface. There is geological evidence for high density rocks (up to 2.65×10^3 kg/m^3) some of which buried at shallow depths of 50–500 m in the Albian shales of this central zone, probably due to intrusion and uplift. Thus, geologically a combination of thinner crust plus density increase in the upper part of the crust, caused by intrusives in the basement and in the sediments is likely to be the best interpretation (Fig. 4). This zone of intrusion and uplift continues NE and SW through the major Abakaliki anticlinorium (Fig. 1). The location of warm springs and hot brines along the axis of the Benue trough are indications that abnormally hot material can be found beneath the trough at comparable shallow depths.

The negative anomalies are ascribed to great thickness of Cretaceous rocks contained within the fault-bounded edges and gravitational interpretation and borehole date indicate the presence of more than 5500 m thickness. The southern trough probably contains as much as 5000 m of Cretaceous rocks in some localities.

Based on geological evidence and gravitational interpretation the following structural history was proposed by Cratchley and Jones (1965). Opening of the Benue trough began prior to marine invasion in the Albian. The mechanism was rifting under tension associated with the separation of South America from Africa. Crustal thinning and graben development at the surface accompanied deposition of perhaps 2000 m of Albian marine shales in a narrow Benue seaway. Uplift of the Abakaliki anticlinorium and the central Benue trough accompanied by intrusion almost certainly occurred in early Cenomanian and gave rise to the central positive anomaly. This was possibly contemporaneous with uplift of the Adamawa Plateau (Le Marechal and Vincent 1970). This is necessary to provide the source material for the 3000 m of continental and deltaic sandstone deposited in the Middle and Upper Benue in the Cenomanian (Carter *et al.* 1963, Offodile 1976) as palaeocurrent directions suggest a highland source to the south and southeast of the trough. Further marine invasion took place in the Turonian and Senonian and during these periods penetrated through the Chad basin via the Maiduguri and Gombe troughs (anomalies 6a and 6b) and probably intermittently into the Doba trough (anomaly 2a) although there is now no direct connection evident into the Doba trough from the Yola arm (Fig. 1) of the Benue. (This has possibly been removed by Tertiary uplift.) Compression of the sediments in the trough into extremely long folds, in the Middle and Upper Benue generally parallel to the rift boundaries began in the Santonian to the SW of the

Benue, and reached the Middle Benue by the end of the Senonian. This occurred at the same time that marine deposition was continuing in the Upper Benue, the Gombe and Maiduguri troughs. This fact appears to us to be extremely important as it implies an anticlockwise rotation of the basement block of Northern Nigeria during the Senonian. Folding in the Gombe trough did not occur until the Maestrichtian. The southern Benue trough was probably closed by Turonian, leaving the northern one as the only possible marine link.

As Bouguer anomalies are affected by topographic elevation, certain areas of negative anomaly (e.g. in the vicinity of Adamawa plateau) which appear on Fig. 2 are considered to reflect isostatic compensation [see Louis (1970) for map of isostatic anomalies].

Anomaly 2—The Doba and Bake–Birao troughs

The Doba and Bake–Birao troughs (anomaly 2a and 2b in Fig. 2) are extremely long (total length is 850 km) sedimentary troughs evidenced by an intense linear negative gravity anomaly.

The Deba trough, marking the western end of the combined feature is approximately elliptical (150 km W–E, 80 km N–S) in shape. Supplementary seismic refraction measurements and electrical resistivity soundings (CPGF 1961, Louis 1970) have indicated sediment thicknesses in the centre of the Doba trough of at least 3500 m. The resistivity interpretation (Fig. 3, profile BB′) indicates a varying sequence of sedimentary rocks ranging from shales or marls to sandstones and grits. This interpretation suggests the possibility of marine or lacustrine deposits as well as continental sandstones. The presence of about 6000 m of predominantly lacustrine deposits with some thin marine intercalations has recently been revealed in an oil exploration borehole near Doba (CONOCO, personal communication). This is suggestive of only limited marine incursions into the Yola arm of the Benue trough, presumably during the Cretaceous, although the major accumulation appears to have been in an intercontinental fault-bounded trough. At the present time, definite geological evidence for a connecting trough between Doba and Benue is missing and the present geological evidence for a connection between the Benue and Doba trough is tenuous. The Bake–Birao trough has a width varying between 40 and 70 km over its 700 km extent to the Sudanese border. It should be noted that this feature was incorrectly marked on the structural map of Africa (UNESCO 1968) published prior to Louis (1970), and unfortunately used in subsequent papers. For a density contrast of 0.6 $\times 10^3$ kg/m^3 between the sediments and the basement rocks, the simple negative anomaly leads to a depth of 3000 m to the basement at Birao.

Separating the Doba and Birao troughs, there is an important positive Bouguer anomaly which corresponds to a high velocity, higher resistive dyke-like body (Fig. 3, profile BB′) and may be related to the faulting and intrusion at Mbere in Cameroun.

Gazel (1956) considers that the age of these faults puts them in the lower Precambrian but that they could have been rejuvenated in a later geological period giving rift troughs similar to those of the Benue and Mbere.

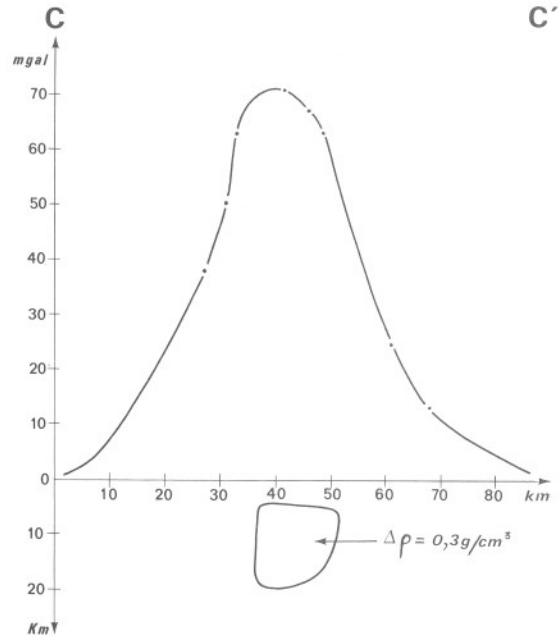

Fig. 5. Profile across Haraz anomaly.

To the north of Doba, a gravity anomaly indicates the existence of a smaller but nonetheless significant trough at Bousso (Fig. 2, anomaly 2c). The Bousso trough extends some 150–200 km in the ESE direction. Its width is about 50 km and the sediments in the trough are about 2000 m thick. From the detailed shape of the gravity anomaly, it can be considered to be a graben.

Anomaly 3—The Haraz positive anomaly

The Haraz Positive Anomaly (Fig. 2, anomaly 3a) is one of the most striking features of the gravity map of the Chad Basin, extending in a generally SW–NE direction as a continuous anomaly for 800 km from Massenya to Ounianga–Kebir (Fig. 1). It can be traced discontinuously to the SW of Massenya across the Cameroun basement for a further 600 km. Attention has been drawn to this feature by Burke and Whiteman (1973) who suggested that it represented the failed arm of a RRR triple function, of which the other arms are the Doba–Bake–Birao trough and the Benue connection via Yola.

The feature certainly appears to be a very important line of fracture. A quantitative interpretation by Louis (1970, pp. 208 and 209) shows that the major part of the mass surplus must lie in a region shallower than 14 km below the surface and be up to 25 km wide. For a density contrast of 0.3 (basalt-basement), which may be realistic as the anomaly occurs essentially over very shallow sedimentary cover (not more than 250 m, west of Haraz, and generally less than 50 m of Chad Formation overlie the basement), the excess mass would have to be approximately 10 km thick (Fig. 5). Other more dyke-like

models are possible. The possible origin of this feature is discussed later. It is sufficient here to say that there is no other evidence to suggest the age which could be Precambrian by comparison with other areas (Louis 1970); Cretaceous, according to Burke's hypothesis; or possibly Tertiary, associated with the Cameroun and Tibesti volcanic zones (Furon 1960).

Other positive anomalies (Fig. 2, anomaly 3b), not individually extensive, occur in a well defined but continuous line for a total distance of 900 km from the vicinity of Maiduguri to that of Largeau (Fig. 1).

Anomaly 4—The Tenere rifts

Gravitational and aeromagnetic anomalies, as well as resistivity soundings have all indicated the presence of three irregular rifts (Fig. 2, anomalies 4a, b, c), all striking approximately NW–SE and possibly extending to the northern and western sides of Lake Chad. The most extensive rift lies to the east and continues to Rig-Rig on Lake Chad; its width varies from 40 to 60 km. The second, near Adrar Madet, is parallel to the first and extends for some 250 km with a width of about 50 km. The third corresponds to the known Tefidet graben. Interpretation of the Bouguer anomaly profiles together with the electrical resistivity sounding results indicate that the graben are filled with at least 3000 m of sediments (Fig. 3, DD′).

Detailed interpretation of resistivity curves (Louis 1970, p. 236) has indicated a variable sequence including probable Middle Cretaceous slides overlain by 1000 m of possibly coarser grained rocks.

On strong geological evidence Fauer (1966) placed the Tefidet trough at the end of the Cretaceous. All the Tenere grabens may have a common origin and age, possibly due to the faulting in Tibesti. It is equally possible that, like similar trending structures in Mali (the Gao trough), they originated in the Precambrian and were rejuvenated during the Cretaceous (Reichelt 1967).

Anomaly 5—Negative anomalies north of Lake Chad

The two linear negative anomalies north of Lake Chad, shown in Fig. 2 as Rig-Rig (anomaly 5a) and Termit (anomaly 5b) are considered to be extremely important grabens linking the Tenere rifts (anomaly 4) to the Maiduguri troughs (anomaly 6a). Although the possibility of basement differentiation had to be considered because of the low gradients on these anomalies, it was discarded on the evidence of resistivity soundings across the feature. An important aspect of the gravity profile when compared to the electrical interpretation is evident from profile EE′ (Fig. 3) which suggests that there is excess mass beneath the centre of the main trough which may be of a form similar to that found in the Benue trough but which is here buried beneath Quaternary sediments. Excess mass beneath the Chad sediments is a typical feature of the area around Lake Chad and southwards toward Garoua and Adamawa (Fig. 1). It serves to complicate the pattern of gravity anomalies due to sediment in-fill, so that it only becomes possible to suggest an interpretation when other evidence from boreholes, seismic determinations or resistivity determination can be invoked. A depth of about 3000 m of sediment, presumably of Cretaceous age, is indicated by the resistivity interpretations on profile EE′ (Fig. 3).

Immediately to the west of Nguigmi (Fig. 1) is another smaller negative anomaly, associated with a trough, which has gradients requiring faulting at the edges of the inferred trough (Fig. 3, profile EE′). These buried rifts have quite clear connections, through a rift system, into NE Nigeria in spite of the lack of data over Lake Chad itself and of the complications of excess mass mentioned above (Figs 1 and 2).

Anomaly 6—Negative anomalies in northeastern Nigeria

Immediately to the SW of Lake Chad, the Maiduguri trough (Fig. 2, anomaly 6a) is confirmed by seismic refraction evidence as well as a gravity low as an important trough, linking anomalies 5 and 1 (Fig. 2). It contains about 3000 m of Quaternary and Cretaceous sediments (profile FF′, Fig. 3) (Cratchley 1960). In the Maiduguri borehole, to the SW of this profile some 1200 m of sediment were penetrated, the lower 600 m being marine shales of Santonian–Maestrichtian age (Carter *et al.* 1963). The basement was not reached. A comparison between the Bouguer anomalies and thicknesses of Quaternary and Cretaceous sediments, where determined seismically and in boreholes, reveals the existence of regional positive anomaly of about 45 mgal running NNE from near Maiduguri and almost certainly continuing to the north of Lake Chad. The excess mass represented by this anomaly may be similar to that found in the Benue trough, i.e. a combination of thinning of the crust and intrusion of basic rocks into the underlying basement and possibly the Cretaceous sediments.

The Maiduguri trough may represent one continuous fracture extending from the Benue trough through Lake Chad to the vicinity of Largeau (Figs 1 and 6). However, there are numerous other positive anomalies near Lake Chad; e.g. at Geidam, which tends to suggest that the structural history of this area is extremely complex and may well have been modified in the Tertiary.

The Gombe trough (Fig. 2, anomaly 6b) represents the continuation of the Cretaceous trough southwestwards to the Benue trough. Possibly faulted beneath sediment cover (as revealed by aeromagnetic data), the Gombe trough is shown by geological and geophysical evidence to contain at least 2000 m of Cenomanian to Maestrichtian rocks at its northern end. Shales of Maestrichtian age appear to be equivalent to the Santonian–Maestrichtian shales found in the Maiduguri borehole (Carter *et al.* 1963). To the west of Gombe, geological outcrops require the presence of at least 600 m of Cretaceous sediments of which about half are marine shales (Carter *et al.* 1963) while gravitational and magnetic

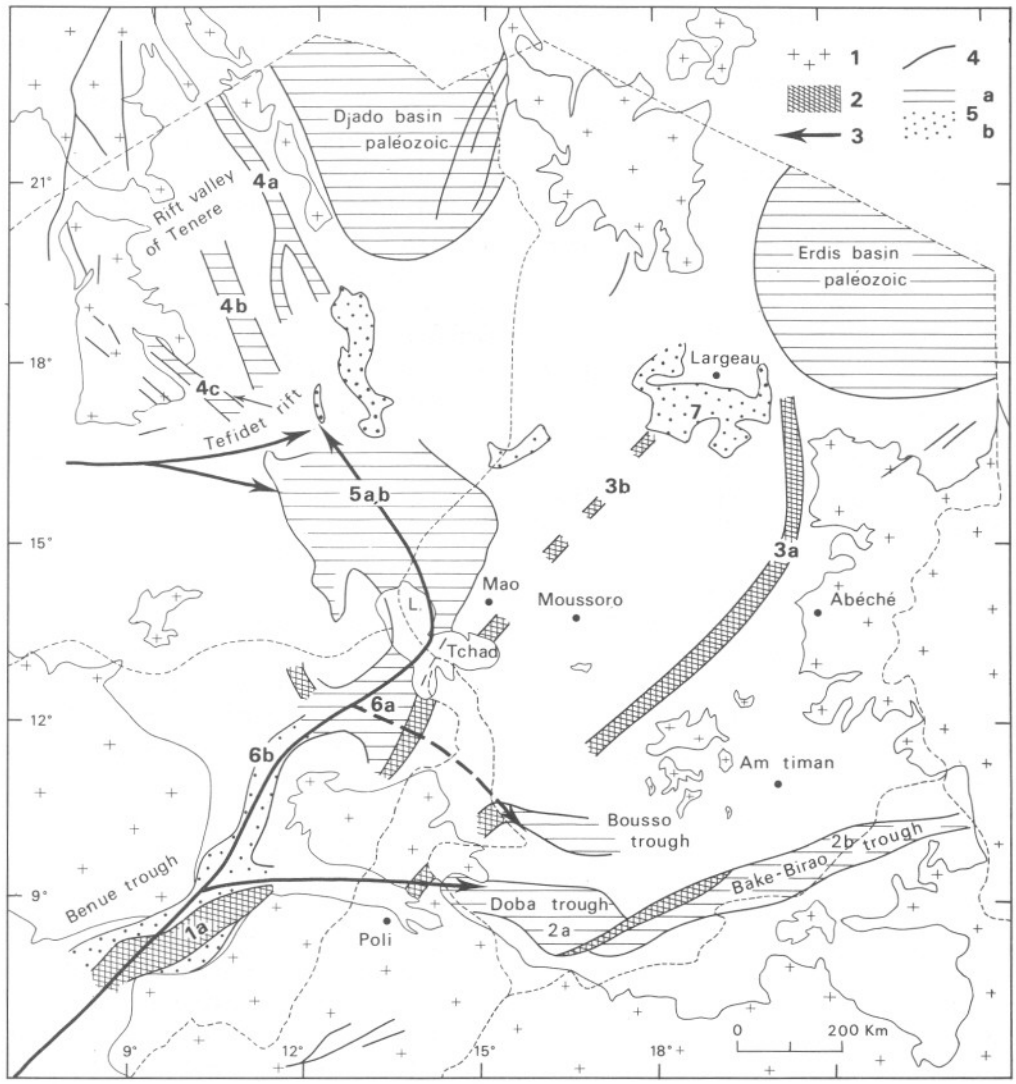

Fig. 6. Generalized interpretation of geophysical results in the Chad Basin. 1—Basement outcrop; 2—zone of probable intrusion; 3—Cretaceous marine transgression; 4—fault; 5a—basement surface >1000 m from several geophysical techniques or from borehole; 5b—basement surface >1000 m from gravimetric survey alone.

evidence suggests the presence of at least 3000 m of Cretaceous rocks. Southwards, the Cretaceous rocks are at least 2000 m thick towards the Upper Benue. To the south of Gombe there is geological and gravitational evidence for at least 5000 m of sediments (Carter *et al.* 1963, Cratchley and Jones 1965, Ajakaiye 1981).

Anomaly 7—Largeau negative anomaly

The large (40 mgal) elliptical negative anomaly which occurs in the northeastern section of the Chad Basin has no obvious connection with other rift anomalies in the Basin. It is quite large, extending to more than 100 km N–S and about 250 km E–W (Fig. 2). Interpretation, in terms of low-density rocks in the basement is possible but unlikely when the maximum variations of 20 mgal, observed along traverses across the basement of the Ouaddai Massif to the east, are considered. It seems quite likely that a sedimentary basin several thousand metres deep may exist here. There is no geological or other geophysical evidence to substantiate this or indicate the possibility of a connection in a SW direction through other less well-defined negative anomalies (Fig. 2) to the trough on the north side of Lake Chad.

SUMMARY OF EVIDENCE

See Fig. 6. The combined geological and geophysical interpretation of data gives strong evidence for a complex series of Cretaceous grabens extending into the centre of the Chad Basin from the SW (Benue) and the NW (Tenere) and bounding its southern edge in the major Doba–Bake–Birao system. In general, negative gravity anomalies are asociated with these features, but complications arise in the Benue trough and around Lake Chad because of the presence of, probably, igneous intrusions and crustal thinning within and beneath the grabens. These give rise to a series of positive gravity features extending in a NE direction from the Benue to the vicinity of Largeau in the NE Chad Basin. A notable positive anomaly (Haraz, Mas-

senya), largely parallel to this direction, is continuous over 800 km of shallow basement and appears to be of Precambrian origin. Some important details are:

(1) Benue trough—associated with the separation of South America and Africa, occurred in Albian time and allowed marine invasion at least as far as Yola (the main arm of the northern section of the Benue trough) in NE Nigeria. Regression in the Cenomian followed uplift, igneous intrusioin and deposition of Continental Bima sandstone. Renewed invasion in late Cenomanian–Turonian time penetrated to the north, towards Maiduguri, to the Chad Basin (marine shales encountered in the Maiduguri borehole). Folding in the Benue trough started during the Santonian while marine deposition was still taking place to the NE.

(2) Doba–Bake–Birao trough—this longer linear feature is infilled with 600 m of presumed Cretaceous sediments. Borehole evidence in the Doba trough indicates essentially lacustrine sediments. Only small amounts of marine sediments were found, consistent with the possible hypothesis that a connecting rift between Yola and Pala was closed (uplift in late Cenomanian?). The extensive eastward continuation—the Bake–Birao trough, may be associated with transient faulting (see proposed model below).

(3) Tenere troughs—the topographical, geological and gravitational expressions clearly indicate graben structures infilled with sediments. Geological evidence in the Telfidet trough indicates Coniacian–Santonian age for the sediments (Faure 1968), i.e. when folding was taking place in the lower Benue. Some basic intrusions occur.

(4) Haraz positive anomaly—this major linear anomaly is interpreted as a basic intrusion into the basement beneath shallow sediment cover. The lack of topographical variation on the basement surface, and of evidence for faulting suggests a Precambrian feature within the peneplained basement, possibly a large intrusive dyke, although it appears to be non-magnetic (Louis 1970).

DISCUSSION OF REGIONAL TECTONICS

Grant (1971) proposed that the Niger delta formed the site of a triple junction of the RRF type, the Benue trough being one of the tensile R arms which partially closed again after the complete separation of South America from Africa. This opening followed by "rebound" due to strain accumulation in the African plate, neatly accounts for the Albian marine invasion followed by compressive folding of the accumulated sediments in the Santonian and later.

Burke *et al.* (1971) suggested a triple junction of the RRR type based on gravity data which indicate oceanic type crust beneath the Niger delta. A Santonian orogeny involving a Benue subduction zone was also proposed—a hypothesis repeated in Burke and Dewey (1974). These two authors (Burke and Dewey 1973) also proposed that early extensional phases of rifting were caused by plume generated triple junctions, citing Louis (1970); Cratchley and Jones (1965) as gravitational evidence for the existence of such junctions at Niger Delta, Chum and Poli (Fig. 6). This interpretation relies on the hypothesis that the Haraz positive anomaly represents an axial rift dyke of Cretaceous age. However, the evidence for both these hypotheses (Benue subduction zone and Cretaceous triple junction associated with the Haraz anomaly) is extremely tenuous (Louis 1978); the Haraz anomaly is quite unlike the other graben anomalies and its geological associations are also quite different. However Burke *et al.* (1971) also suggested relative movement within the African plate due to differences in spreading rate and direction between the section of the mid-Atlantic ridge opposite the bulge of Africa and that south of the Gulf of Guinea. We support this concept as it can explain some of the features of the Doba trough system, and the possible link between these and transform faults via the Ngaundere fault.

Burke (1976) proposed that the Cretaceous rift system beneath the Quaternary sediments of the Chad Basin helped to localize this major basin, an idea with which we agree. Unfortunately, he again associated the Haraz anomaly with a Cretaceous axial rift dyke.

Wright (1976) compared oceanic fracture zone alignments identified by Francheteau and Le Pichon (1972) with mapped continental fracture systems. The evidence for continuity in these structures is striking, particularly for the Romanche and Chain transcurrent fractures, and the mapped faults show dextral movements of 10 and 30 km. There is also tentative evidence in this paper for the possible continuation of the Charcot faults, and perhaps other mid-Atlantic transform faults further south of Charcot (Fig. 1), into the African continent to possibly as far as the Mbere–Ngaundere fault system.

Benkhelil (1982) has presented a hypothesis linking the Romanche, Chain and Charcot faults directly into the Benue trough in order to postulate a "pull apart basin" model for sedimentation in the Benue. We find this model unconvincing as there is presently lack of evidence for the cross-faults that are required to bring all three major transcurrent fractures within the confines of the Benue, and indeed, this model is not consistent with the clear evidence in Wright (1976). It is also difficult to visualize how marine invasion could have taken place under this hypothesis.

In conclusion, we propose a chronological model for the evolution of this area:

(1) Precambrian:

Features in the basement; a particular example of which is the major anomaly of Haraz. This anomaly could represent the boundary of a continental plate inside the Precambrian but certainly before the Pan-African.

(2) Cretaceous:

(a) The history begins by the opening of the Atlantic with a triple junction RRF (in agreement with Grant 1971): a small extension in the Benue trough gives a failed arm; the transform faults (arm F) Romanche and Chain fractures zones, are controlled by pre-existing lines of weakness in adjacent continental crust (Nigeria

for Romanche and Chain, Ngaundere fault system for the Charcot fracture zone) (Wright 1976). These pre-existing lines of weakness were probably established during the Pan-African orogeny but these faults may well represent lineaments of much greater age (MacCurry 1971). During the opening of the South Atlantic, these transform faults were active and resulted in a rejuvenation of the fault system in the continent. In particular, the Ngaundere fault system shows a pattern of transcurrent movement whose extension into the continent may be represented by the Bake–Benue trough.

Another interpretation is possible: when considered as a unit, the Doba and Bake–Birao troughs are aligned in a direction different from that of the Bake–Birao trough alone. This alignment corresponds to a major lineament through Africa, running from the Gulf of Guiinea coast to the coast of the Gulf of Aden. This lineament could be of Precambrian origin which has been reactivated during the separation of Africa and South America (Louis 1970).

(b) Further marine invasion took place in the Benue trough (Turonian and Senonian for the Middle Benue) and during these periods extended to the Chad Basin and probably from time to time into the Doba trough. Compression of the sediments (end of Senonian in the Middle Benue) is an indication of the closure that occurred in the Benue trough during this period. During this time, the Tenere troughs appeared, while the Tibesti exhibited the first occurrences of fracturation and the Djado was subjected to a brittle tectonic. We must admit that during a short period, an extension phase in the East of Niger is contemporaneous with the Benue closing. We suggest that stresses which generated these events came from the "collision" of European and African plates in the North. In order to explain the gravity anomalies in the Benue trough and also in the centre of the Chad Basin (near the lake) we must assume a fairly high density basement with a possible crustal thinning. Such phenomena related to the formation of grabens could explain the subsequent importance of sedimentation in the basin (Burke 1976).

(3) Tertiary:

(a) Uplift and volcanism appear in the Cameroun and in the Tibesti. The uplift could possibly have obliterated traces of the link between the Yola arm of the Benue into the Doba trough.

(b) Further sedimentation continues in the Basin.

More geophysical and geological data is still required for a better understanding of the tectonics of the Chad Basin. In particular, the results of seismic reflection profiling of the deep crust, deep drilling and geochronology of the basement around the basin would be very useful for this purpose.

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