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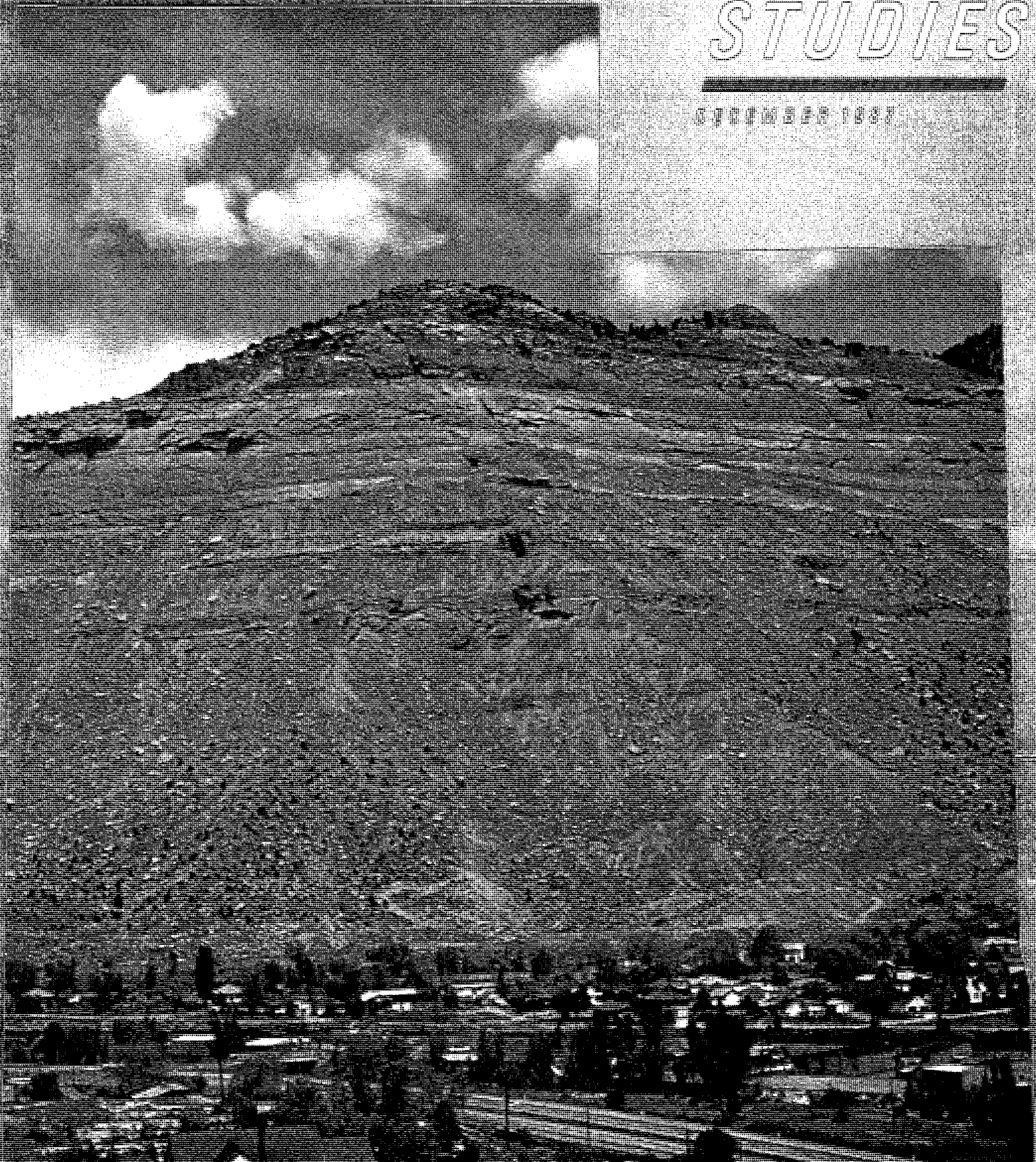

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Cover: Cretaceous coal-bearing rocks near Price, Utah

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Geologic Modeling of a Gravity Line from the Central African Rift System, Sudan

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ABSTRACT

Gravity data acquired over approximately 285,000 square kilometers in east central Sudan reveal the presence of four major parallel NW–SE-trending gravity lows. These anomalies are produced by covered rift basins that are considered to be part of the Central African Rift System.

Anomaly separation showed that highs in the regional gravity field occur over basins, a feature interpreted to result from crustal thinning coupled with passive mantle uplift. Residual gravity modeling indicates maximum depths to basement of approximately 1550 m for the shallowest basin and approximately 4200 m for the deepest basin. The models together with observations made from seismic data demonstrate the dominance of half-grabens in the rifts. Calculations made from regional gravity models and seismic data indicate a cumulative crustal extension of approximately 12–14 km for the four rifts that have a combined width of approximately 210 km.

Rifting originated through the mechanical, isostatic, and thermal responses associated with crustal extension and lithospheric thinning produced by regional tensile stresses. Stretching was accommodated in the brittle upper crust by listric normal faulting. Crustal thinning coupled with passive upwelling of the more ductile upper mantle and lower crust lead to isostatic and thermal subsidence. Geophysical and geological data indicate that regional subsidence has been the general epeirogenic response during and after rifting.

Age of rifting is considered to be Cretaceous, although the relative time of rifting between the major basins remains an unanswered question. Truncation of the rift basins along their northwestern ends supports an earlier hypothesis that the Central African Shear Zone continues through this region of the Sudan.

INTRODUCTION

Major progress in the delineation of rift basins in the interior of the Sudan has resulted from hydrocarbon exploration efforts of several oil companies. Beginning in 1975, Chevron Overseas Petroleum initiated exploration of a 518,000 km^2 area in southern Sudan starting with the acquisition of aeromagnetic data and followed by the acquisition of gravity and seismic data (Flege 1982, Nicod 1982). The discovery of a series of rift basins, collectively referred to as the Southern Sudan Rift and White Nile Rift (southern portion), resulted from these surveys (Browne and Fairhead 1983, Browne and others 1985, Fairhead unpubl. manu., Flege 1982, Nicod 1982, 1983). Using the same sequence of data acquisition, a consortium of oil companies consisting of Sun Oil Company, Marathon International Oil Company, Ocelot Industries, and the General Petroleum Corporation of Sudan has obtained aeromagnetic, gravity, and seismic data covering a 285,000 km^2 area of central Sudan centered about Khartoum in the Nile drainage basin.

This study deals with one gravity profile that extends 660 km across the area covered by the consortium's data. As a result of the surveys, several structural features, interpreted as rifts, were delineated. Gravity data have proven to be an effective tool in outlining these basins. The profile selected for analysis runs normal to all of the major rifts within the study area.

A thesis submitted to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science, March 1986.

A major objective of this study is to relate deep crustal structure, as determined by the extraction and modeling of the regional gravity field, to the rift basins, as determined by the modeling of the residual gravity field. The relationship between the rifts and regional crustal structure is then assessed in light of previously postulated rift mechanisms (Jarvis 1984, Jarvis and McKenzie 1980, McKenzie 1978). Calculations of crustal extension were made independently from regional gravity models and seismic data. Although only one gravity profile is presented here, the author had available to him several hundred kilometers of seismic reflection lines covering all the major basins, and aeromagnetic data covering the entire study area. The data allowed constraints to be placed on both the regional and residual gravity models, and on the calculations of crustal extension. Observations of rift geometries made from the data and from residual gravity models are cited and discussed in terms of recently presented models for the evolution of structural styles in rift basins (Bosworth 1985a).

Using the residual gravity models, calculations of crustal extension, postulated rift mechanism, and rift geometries, a regional geologic model is proposed and related to the regional paleotectonic setting.

LOCATION

The Sudan, together with some of the major cities and rivers, is shown in figure 1. The outlined window centered about Khartoum shows the study area and corresponds to the border of figure 2. Figure 2 shows the gravity survey stations and the position of the gravity profile (A-A′) used for this study. Latitude and longitude coordinates, based on a Clarke 1880 spheroid, for the endpoints of the profile are 12.55°N, 31.14°E, and 17.42°N, 34.69°E for A and A′ respectively.

PREVIOUS WORK

General treatments of the geology of the Sudan are available from various sources (Andrew 1948, Furon 1963, Vail 1978, Whiteman 1971a, 1971b). A regional Bouguer gravity map of Africa has been published by the United States Defense Mapping Agency (Slettene and others 1973). This publication outlines very broad wavelength features in the study area, exclusive of the rift anomalies discussed in this paper. The data has been incorporated into regional studies that include sections of the Sudan (Brown and Girdler 1980, Brown and others 1980, Fairhead 1979, Girdler 1975). Brown and Girdler (1980) have reported the results of a gravity traverse across northern Africa conducted in 1975 by the British army and air force. The survey started in Darkar, Senegal, ended in Cairo, Egypt, and traversed through northern Sudan. Both the Bouguer anomaly map of Africa and the data reported by Brown and Girdler provided information concerning the nature of the background gravity field in the Sudan.

As previously discussed, the delineation of rift basins within the interior of the Sudan has resulted from the exploration efforts of several oil companies (Browne and Fairhead 1983, Browne and others 1985, Fairhead unpubl. manu., Flege 1982, Nicod 1982, 1983). While the majority of the collected data remain proprietary, some data have been made available to various authors. Workers at the University of Leeds have published articles concerning the rifts and other tectonic features in southern Sudan using a combination of public domain data and Chevron gravity data (Bermingham and others 1983, Browne and Fairhead 1983, Fairhead unpubl. manu.).

Of the basins discussed in this paper, the southernmost—called here the Bara Basin of the White Nile Rift—has been previously discussed in the literature. The earliest recognition of this basin came as a result of gravity surveys conducted in an effort to locate favorable areas for groundwater exploration (Ali and Whitely 1981, El Shafie 1980, Khattab 1975, Mitwalli 1969, Strojexport 1977). On the basis of these and other data (Browne and others 1984, Chevron unpublished data), Browne and others (1985) studied the White Nile Rift. The major emphasis of this work was on the Bara Basin arm of the White Nile Rift in a region to the southeast of the study area. The results of a gravity, electrical resistivity, and seismic refraction survey covering the area to the immediate southeast of the study area has also been published (van Overmeeren 1981).

The present-day seismicity of the region has been studied by various workers (Browne and others 1985, Fairhead and Stuart 1982, Qureshi and Sadig 1967). These investigations have demonstrated that the rift system in the Sudan is seismically quiet in comparison to the East African rift system. Browne and Fairhead (1983) have proposed that the lack of seismicity in the Central African Rift System suggests that it is either locked, or is developing at slow rates with stresses being released at microseismic levels.

The work by Omer (1975, 1983) and Aboul Ela and Mabrouk (1978), dealing with the stratigraphy of shallow sediments in some of the basinal areas, proved useful in the regional geologic model developed from the gravity data and provided useful information in assessing the age of rifting. Water-well data, used to provide constraints on regional gravity anomaly separation, was obtained from the Sudan Geological and Mineral Resource Department by a co-worker at Marathon International Oil Company.

METHODS

The gravity profile trends N. 35° E., runs normal to the major rift basins under study, and traverses the basins at locations encountering maximum gravity lows. This orientation, in combination with the elongate nature of the rifts, allowed two-dimensional gravity algorithms to be used for modeling both the regional and residual gravity fields. The software used for modeling the residual gravity field was developed by EDCON, Inc. (Exploration

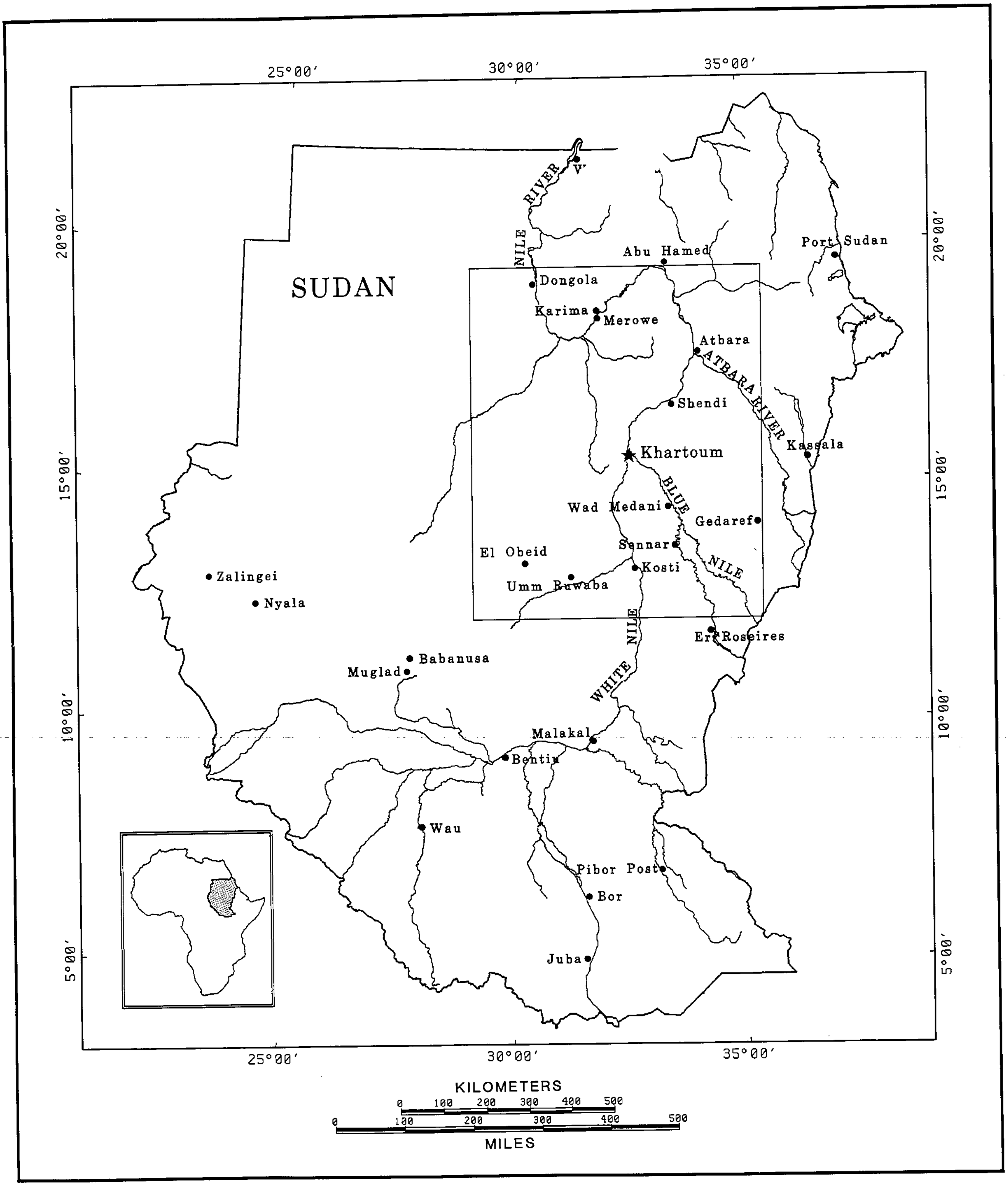

FIGURE 1.—*Sudan country index map. Windowed area centered about Khartoum shows the study area and corresponds to the outline of figure 2.*

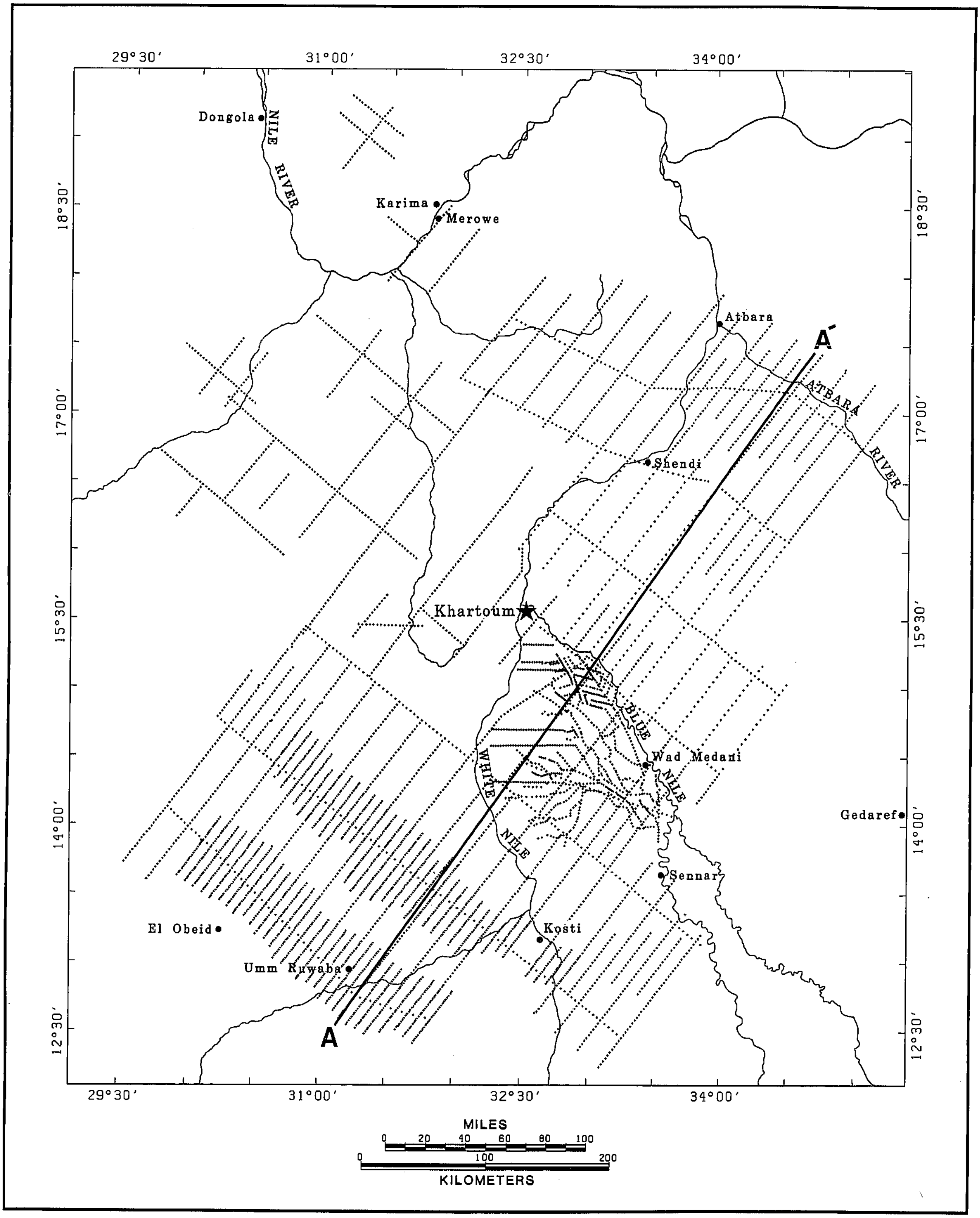

FIGURE 2.—*Study area, gravity survey base map (+ indicates location of gravity station), and location of profile A-A′. The location of the profile was chosen so as to traverse normal to the major rift basin axes at positions where maximum gravity lows were encountered.*

Data Consultants). The program incorporates an interactive forward modeling scheme based on a Talwani-type algorithm (Talwani and others 1959) that utilizes a line integral method for calculating the gravitational effect of two-dimensional masses, as first described by Hubbert (1948).

Modeling of the deep crustal structure, using the regional gravity field for control, was performed using an automatic inversion method that utilizes fast Fourier transform techniques (Parker 1973). This modeling program was developed by Three-D Gravity, Inc.

Additional algorithms developed by Three-D Gravity, which also utilize Fourier transforms, were used for upward continuation, spectral analysis, and bandpass filtering of the Bouguer gravity to help assess anomaly separation. Derivative calculations were also performed on the residual gravity using similar techniques.

The gravity control points shown in figure 2 were used to generate a 4 km square, gridded map surface of the Bouguer gravity by use of a moving least-squares gridding algorithm. Gravity values were then back-interpolated from the gridded surface onto nodes spaced 3.3 km apart along profile A-A′ to produce the Bouguer gravity profile.

Least-squares polynomial fitting of the Bouguer gravity was performed to evaluate the regional and background gravity fields. The algorithm used incorporated Gaussian elimination with backward substitution.

Seismic sections available from each of the major basinal areas were used to calibrate the regional gravity field over the basins. The sections were first depth converted using an AIMS (Advanced Interpretive Modeling System) modeling algorithm developed by GeoQuest International, and then gravity modeled using the two-dimensional forward algorithm discussed above. Densities of intrabasin rock units used in the residual gravity models were derived using interval velocities and Gardner's formula (Dix 1955, Gardner and others 1974).

GRAVITY DATA

The gravity profile that forms the basis of this study was taken from a collection of Bouguer gravity values acquired in three phases over the study area (fig. 2). The dominant NW–SE rift trend was delineated prior to initiation of the gravity survey using existing geologic, water-well, and aeromagnetic data. Knowing the major structural trend allowed the gravity survey to be designed with the bulk of the survey lines running normal to the rift axes and to have an increase in station density in rifted regions.

Acquisition

In the first phase of the gravity survey, 4,777 gravity readings were taken along most of the NE–SW- and NW–SE-trending lines in figure 2. An area of approximately 218,000 km^2 was covered. Station locations were determined by tying into a network of 17 primary location control points that were established using a JMR-1 satellite navigation system. Secondary control points were also established at the endpoints of the survey lines. Elevations at the control points were determined by tying into established benchmarks using microbarometric altimetry. Instrumental drift and changes due to atmospheric variations occurring between the time of reading at the benchmarks and control points was monitored using a second barometer at nearby base stations. Transportation between gravity stations was accomplished using a Hughes 500D helicopter. Latitude, longitude, and elevation of each station was determined from two inertial navigation systems mounted on the aircraft. Satellite navigation stations at line ends served as calibration points for the inertial systems.

In the second phase of the survey, 819 gravity readings were taken along a series of roads and canals in the Gezira area southeast of Khartoum, seen as the irregular pattern of stations between the White and Blue Nile Rivers on figure 2. Lateral location control was provided by taking the gravity readings at cultural points whose positions could be determined using existing topographic maps. Elevations were measured using barometric leveling relative to an established base station.

In the third phase of the survey, 581 readings were taken over an approximately 67,000 km^2 area northwest of Khartoum, seen as the widely spaced lines on figure 2. Station locations were determined using satellite navigation control points on the ends and midpoints of survey lines. Interpolation between control points was done using vehicle odometer readings and compass bearings. Elevations were measured using barometric leveling tied to previously established benchmarks.

The first phase of the survey has an accuracy of 0.5 mgal, based on repeated station readings and the amount of error introduced due to inaccuracies in the parameters involved in data reduction. Accuracy for the second and third phases was approximately 1.0 mgal based on the same criteria. A mistie check on the intersection points of the three surveys indicated agreement to within approximately 1.0 mgal.

La Coste-Romberg gravity meters were used to acquire all of the data. All readings were tied to the Khartoum P absolute gravity station through a network of base stations established throughout the study area prior to initiation of the survey. The Khartoum P base station is located at the survey offices of the Geological and Mineral Resources Department and has an absolute value of 978,302.79 mgal on the Potsdam datum (Isaev and Mitwalli 1974).

Data Reduction

Gravity readings from all three phases of the survey were processed in an identical manner. Bouguer, free-air, latitude, tidal, drift, and terrain corrections were applied to the observed readings. Datum of reduction was mean sea level, and the Bouguer correction utilized a density of 2.35 g/cm^3. Latitude corrections were calculated using the 1930 International Gravity Formula. Terrain corrections were of minor concern in most regions due to the flat topography, but were made using Hammer zones (Hammer 1939) where necessary. Tidal corrections were calculated using tables available from the USGS for worldwide use. A formula supplied by the British Geological Survey was used for tidal corrections during the third phase of the survey. After tidal variations were removed, instrument drift corrections were applied.

The final gravity data base covers an area of approximately 285,000 km^2. The accuracy of the readings was more than sufficient to meet the objective of the survey, that being the delineation of large-scale structural features having gravity variations of up to approximately 50 mgal.

Datum Shift

For the purposes of this study, the gravity data base was shifted from the Potsdam datum to the International Gravity Standardization Network (IGSN 71) datum, using a −14.0 mgal shift together with a reapplication of the latitude correction using the 1967 Geodetic Reference System Formula (Woollard 1979).

Gravity and Elevation Profiles

The entire data set was used to generate a gridded map surface of Bouguer gravity values. Grid node spacing was set at 4.0 km. Bouguer values were back-interpolated onto profile A-A′ with nodes spaced 3.3 km apart. The resulting Bouguer gravity profile is illustrated in figure 3 together with the terminology used throughout the text in identifying the major structural features. Gravity values range from −79.1 to −22.67 mgal. The rift basins crossed by the profile are the Bara and Kosti Basins (White Nile Rift), Khartoum and Khartoum South Basins (Blue Nile Rift), and Atbara Basin (Atbara Rift). These rift basins constitute all of the major structural lows delineated by the gravity survey. Other minor structural lows are suggested by the gravity data and are currently under investigation to ascertain their significance. None of these features, however, are traversed by profile A-A′.

An elevation profile along A-A′ demonstrating the flat topography is shown in figure 4. Elevation ranges from 360 to 578 m with the only major relief occurring over a range of hills between km 410 and 570.

There is little, if any, surface expression of the rift basins. The Atbara River lies at the northern edge of the Atbara Basin, suggesting possible fault control for its position.

GEOLOGIC SETTING

A generalized geologic map of the Sudan is illustrated in figure 5 (after Geologic Map of the Sudan, Geological and Mineral Resources Department, Khartoum, 1981).

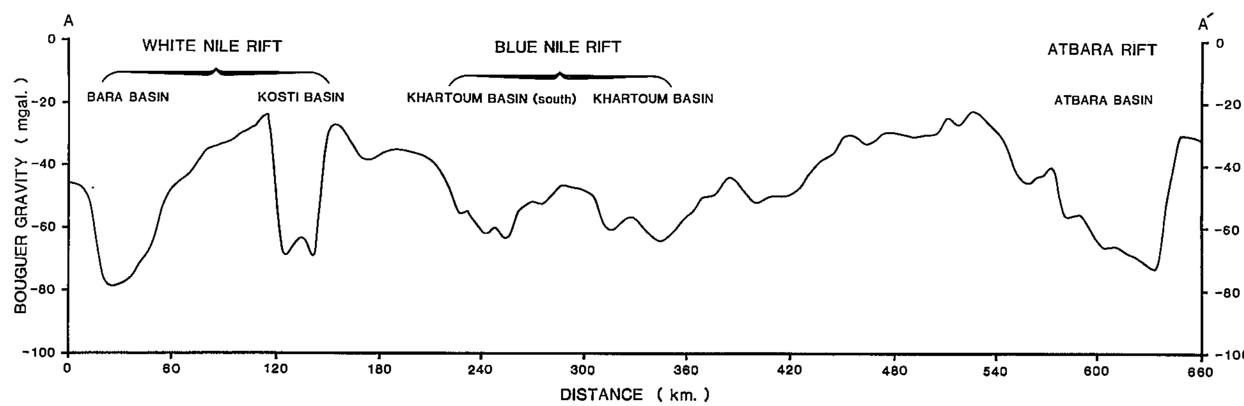

FIGURE 3.—*Bouguer gravity field along profile A-A′. Terminology used throughout text in identifying rifts and basins is also illustrated. The Bara Rift Basin and Kosti Rift Basin are here collectively referred to as the White Nile Rift, the Khartoum South and Khartoum Rift Basins are referred to as the Blue Nile Rift, and the Atbara Basin as the Atbara Rift. Gravity values range from −79.1 to −22.7 mgal on the IGSN datum.*

The position of the gravity profile is marked as the heavy dashed line trending NE–SW east of Khartoum.

The profile begins in the southwest in undifferentiated basement rocks along the northeastern edge of the Nuba Mountains. After traversing a major fault, the line extends across an approximately 125 km wide NW–SE-trending swath of Cenozoic sediments. The surface sediments in this region consist mainly of unconsolidated clays, silts, sands, and gravel of the Tertiary and Quaternary Umm Ruwaba and Gezira formations (Vail 1978). The end of this swath of sediments is marked by a second major fault northeast of which the profile crosses another section of undifferentiated basement complex. After traversing a third major fault, a second NW–SE-trending swath of Cenozoic sediments approximately 150 km wide is encountered. The surface sediments in this region are also of the Umm Ruwaba and Gezira formations. Continuing past this section the profile traverses a large area of Mesozoic sediments, mapped as the Cretaceous Nubian Sandstone, and ends north of the Atbara River once again in undifferentiated basement complex.

A rough correlation exists between the three faults traversed by the profile and major gradients in the Bouguer gravity field. The southernmost fault corresponds approximately with the southern edge of the Bara Basin, the second fault with the northern edge of the Kosti Basin, and the northernmost fault with the southern edge of the Khartoum South Basin. It should be noted that this correlation holds in the areas where the profile traverses the faults and, whereas the gravity data for the whole region supports NW–SE trends of faulting, the exact delineation as shown on the geologic map is not supported. Undifferentiated basement complex is a widely used term in Sudan for describing igneous, sedimentary, and metamorphic rocks of assumed Precambrian age. Shadul (1978) has determined that the major components of the basement complex in central Sudan are granites, granite gneiss, and schists.

TECTONIC SETTING

On a regional scale, the rift basins under study lie on the eastern side of a series of structural features collectively referred to as the Central African Rift System (Bermingham and others 1983, Browne and Fairhead 1983, Fairhead unpubl. manu.). Figure 6 illustrates the major tectonic elements of this rift system that extends from the Benue Trough in Nigeria to the Atbara Rift in eastern Sudan. Major components of this system include the Benue Trough in Nigeria, the Adamaoua Dome and Mbere-Djerm Basin in Cameroon, the Bousso and Doba Basins in Chad, the Bake-Birao group of basins in southern Chad and north Central African Republic, the Darfur Dome and Baggara Basin in western Sudan, and a series of NW–SE-trending rift basins in Sudan. The axial trends of the rift basins in Sudan as shown on figure 6 are well defined from magnetic, gravity, and seismic data, but should be viewed as the overall trends of a whole series of individual rifts and sub-basins rather than contiguous structural features.

The WSW–ENE trend of basins and faults extending from Cameroon to western Sudan is referred to as the Ngaoundere (or Foumban) Lineament (Browne and Fair-

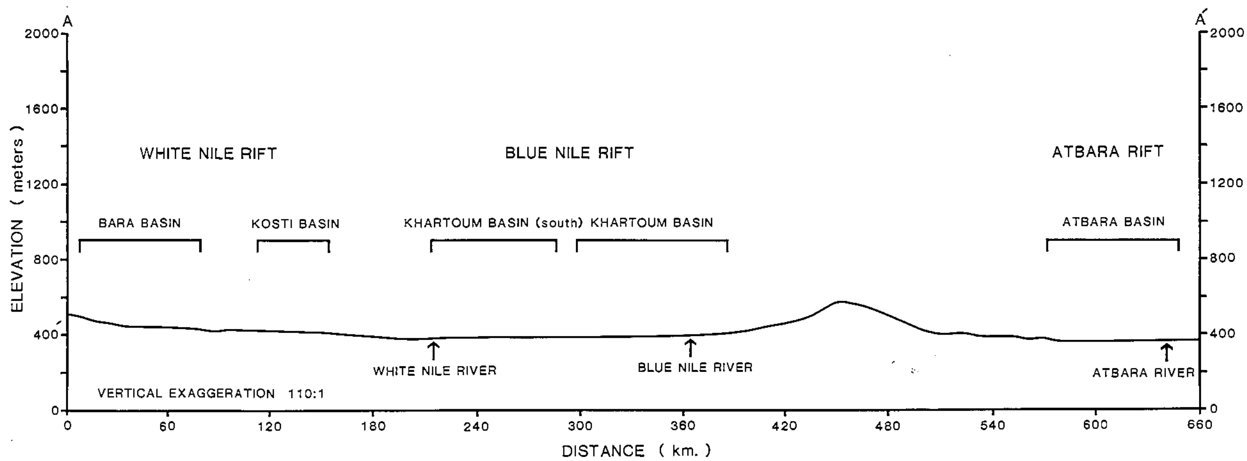

FIGURE 4.—*Elevation along profile A-A'. The profile demonstrates the flat nature of the topography (note the vertical exaggeration) and the lack of surface expression of the rift basins. The elevation ranges from 360 to 578 m with the majority of relief occurring over a small group of hills between km 420 and 500. The subtle depression through the Nile drainage system is centered over the Blue Nile Rift.*

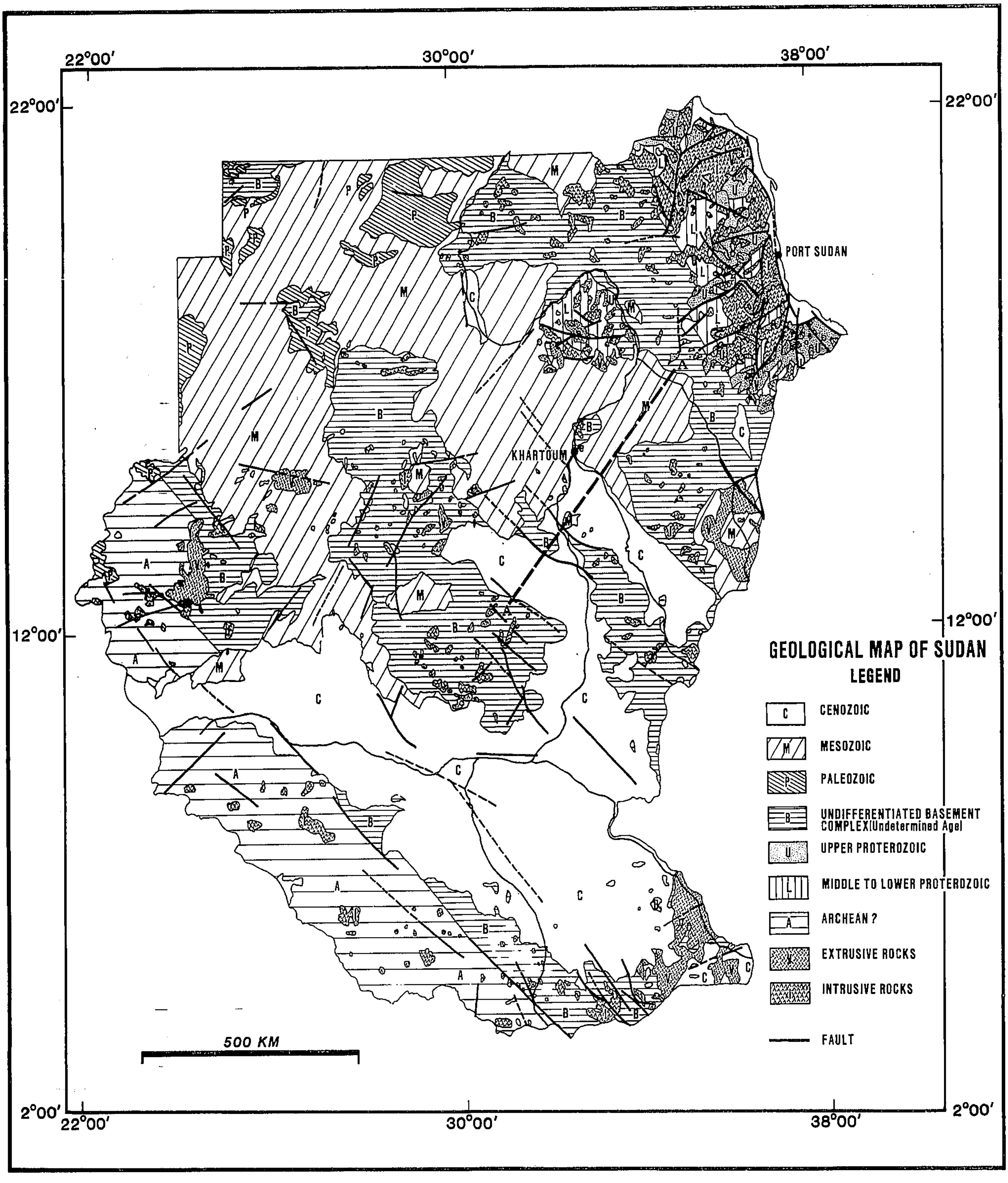

FIGURE 5.—*Simplified geologic map of Sudan with location of profile A-A' (after Geologic Map of the Sudan, Geological and Mineral Resource Department, Khartoum, Sudan, 1981).*

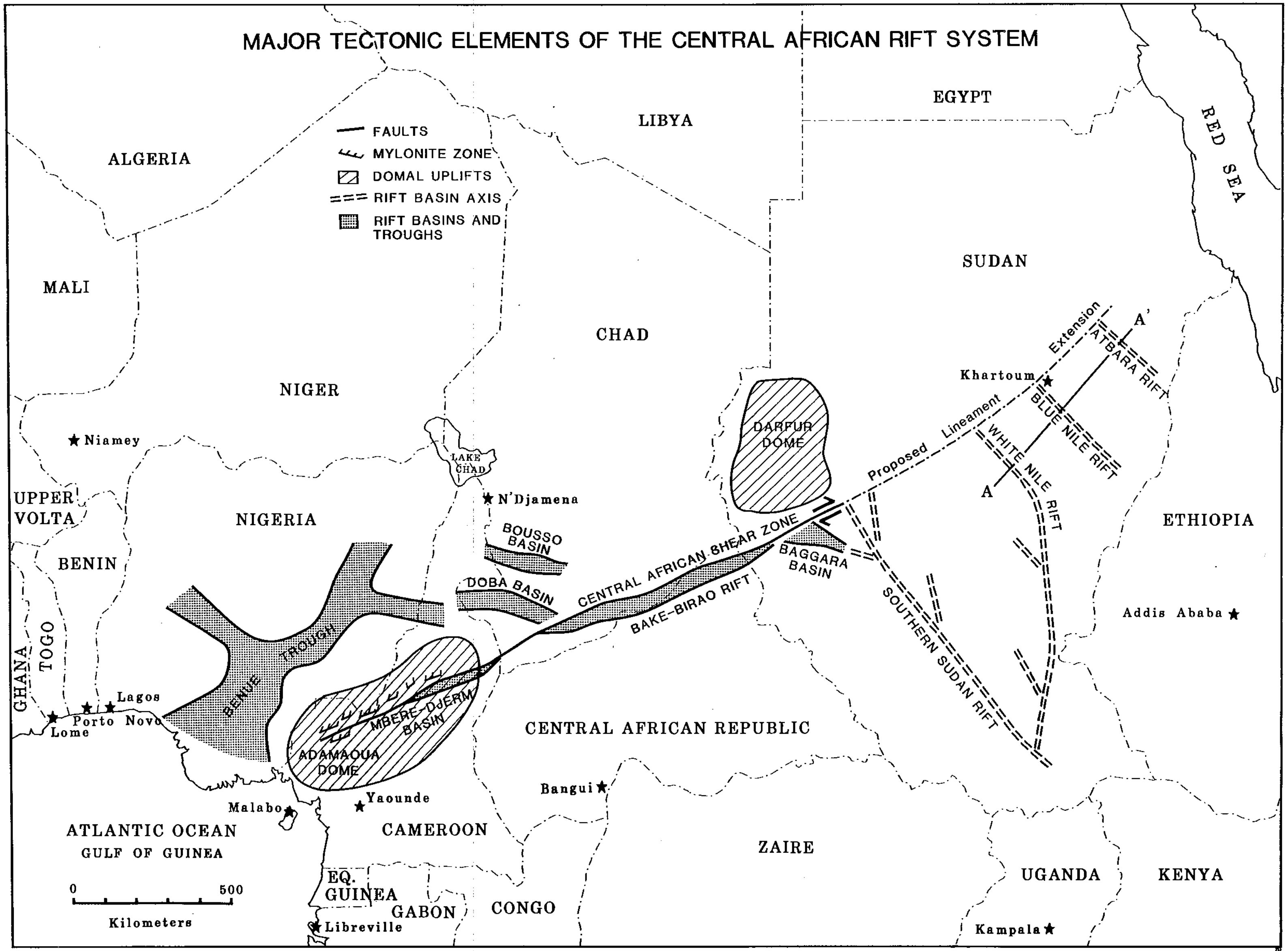

FIGURE 6.—*Generalized map showing the major tectonic elements of the Central African Rift System including the axial trends of the southern and central Sudan rifts. Position of profile A-A′ is shown and runs normal to the White Nile, Blue Nile, and Atbara rift basins. The ENE–WSW trend of faults and basins is referred to as the Ngaoundere lineament (Browne and Fairhead 1983), is shown to have a dextral shear component (Browne and Fairhead 1983, Cornacchia and Dars 1983), and has been referred to as the Central African Shear Zone (Browne and others 1985, Fairhead unpubl. manu.).*

head 1983). Bedrock mapping in Cameroon (Lasserie 1961, cited in Browne and Fairhead 1983) has delineated major mylonite zones along basement faults aligned with the Ngaoundere (Foumban) lineament. De Almeida and Black (1967, cited in Browne and Fairhead 1983) have shown the lineament to be part of a dextral shear zone that formed during the Pan-African orogeny. Cratchley and others (1984) have proposed that the lineament marks the extension onto the continent of major oceanic fracture zones, the trend and location being controlled by preexisting zones of weakness possibly established during the Pan-African orogeny. Martin and others (1981), in making a revised fit of South America to south central Africa, have shown the lineament to align with the Pernambuco dextral transcurrent fault system in Brazil, suggesting the lineament predates Mesozoic continental separation. Dextral shear motion along the lineament is supported by Cornacchia and Dars (1983), who have reported dextral movement of 40 km along faults paralleling the lineament near Bozoum in northwestern Central African Republic. Reactivation along this lineament during the Cretaceous acted to control the development of many of the structural features of the Central African Rift System. Browne and others (1985) have extrapolated this lineament across Sudan (the proposed lineament extension on fig. 6), crossing at the northwest terminations of the Southern Sudan, White Nile, Blue Nile, and Atbara Rifts, and have proposed that the Baggara basin marks the continuation of this zone into Sudan, the basin itself produced by dextral shearing. The lineament is believed to represent a major zone of crustal weakness in central Africa and is inferred to have been a recurrent, dextral, strike-slip zone throughout major episodes of central African geologic history, particularly during the Creacteous and Tertiary, and is referred to as the Central African Shear Zone (Browne and others 1985, Fairhead unpubl. manu.).

Evidences cited by Browne and others (1985) that support the continuation of this lineament into Sudan include (1) the termination of rift basins at their northwest ends along the projected location of the lineament; (2) the change in the trend of major faulting (see fig. 5), with NW–SE faults dominating to the south of the lineament and NE–SW faults dominating to the north of the lineament; (3) the northwestern termination of Cenozoic sediments (see fig. 5); and (4) the alignment of volcanic centers along the north side of the lineament, extending from Jebel Marra in the Darfur Swell to the Bayuda Desert (immediately northwest of Atbara) (Browne and others 1985, Fairhead unpubl. manu., Francis and others 1973, Vail 1978). Gravity and magnetic data from the study area also support the extension of this lineament into central Sudan based on the termination of the major rift basins on their northwest ends as indicated by gravity and on a marked change in the frequency content of the aeromagnetic data along the proposed lineament extension.

BACKGROUND GRAVITY SETTING

Figure 7 shows the position of profile A-A′ on a simplified version of the Bouguer gravity anomaly map of Africa produced by the United States Defense Mapping Agency (Slettene and others 1973). This map illustrates broad wavelength regional features indicative of a deep source for the causative body. Two main sections are commonly delineated, the "great negative Bouguer anomaly" over the southern half of the continent, and the "lesser negative Bouguer anomaly" seen as the northwesterly trending arc extending through the northern half of the continent connecting the Cenozoic volcanic centers of Jebel Marra (in Sudan), Tibesti (in Chad), Hoggar (in Algeria), and Air (in Niger) (Brown and Girdler 1980, Brown and others 1980, Girdler 1975). Figure 8 shows the central portion of the lesser anomaly that runs from the Zaire-

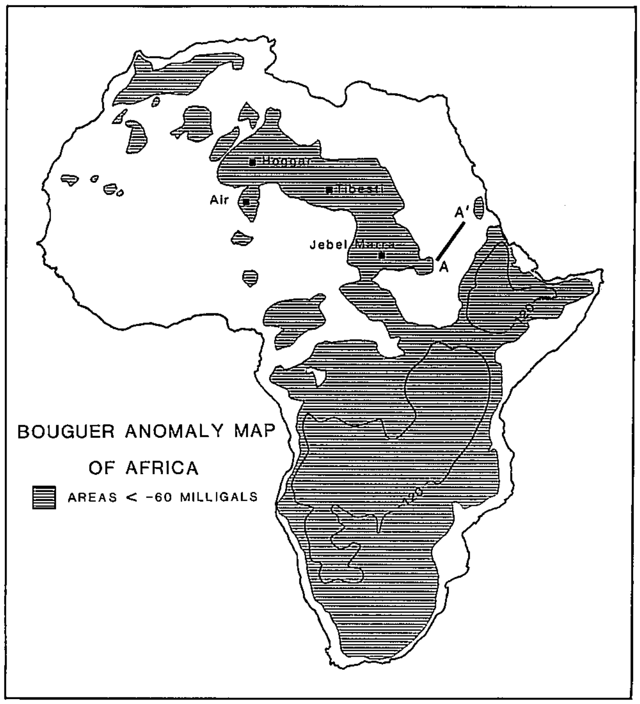

FIGURE 7.—*Simplified map of the Bouguer anomaly of Africa (after Slettene and others 1973). The shaded region shows anomalous areas with Bouguer values less than –60 mgal. Two main divisions of the anomaly are the "great negative Bouguer anomaly" covering the southern half of the continent and the "lesser negative Bouguer anomaly" seen as the northwesterly trending arc over the northern half of the continent (Brown and others 1980, Girdler 1975). Bouguer values in the greater anomaly reach a maximum low of approximately –240 mgal while the maximum low in the lesser anomaly is approximately –120 mgal.*

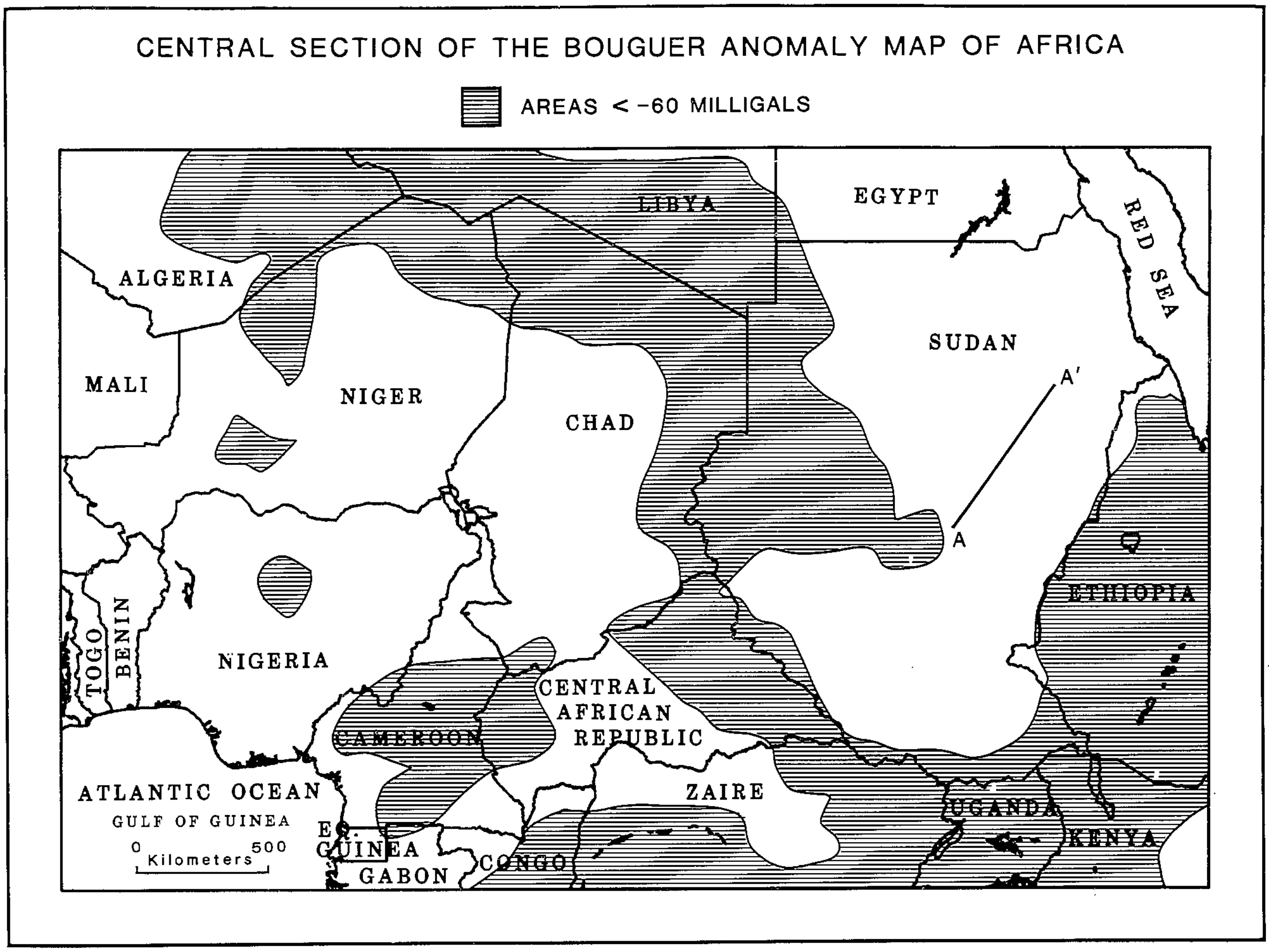

FIGURE 8.—*Central section of the Bouguer anomaly of Africa (after Slettene and others 1973). The lesser anomaly, which is commonly explained in terms of deep lithospheric thinning and associated upwelling of the asthenosphere (Brown and Girdler 1980, Brown and others 1980, Crough 1981, Fairhead 1979, Girdler 1975), is seen extending along the western border of Sudan. The small rounded low at the immediate western end of profile A-A' is related to the Nuba Mountains.*

Uganda-Sudan border junction to Algeria. These anomalies have generally been explained in terms of lithospheric thinning with associated asthenospheric uplift (Bermingham and others 1983; Brown and Girdler 1980; Brown and others 1980; Crough 1981; Fairhead 1976, 1979; Girdler 1975). Of particular interest is the offset and necking that occurs around the Chad-Sudan-Central African Republic border junction at a position corresponding to the Central African Shear Zone (see figs. 6 and 8). This regional picture places the rift basins under study on the eastern flank of, and approximately parallel to, a major zone of lithospheric thinning, an important implication to consider when postulating the mechanism for rifting.

An important observation made from figures 5 and 6 is the strong correlation between the trends and positions of the rift basins and areas of Cenozoic sedimentation. This correlation also plays an important role in speculations of rift mechanisms.

REGIONAL GRAVITY AND ANOMALY SEPARATION

Essential to the objectives of this study was the extraction, from the Bouguer gravity, of a regional gravity field. The regional field sought is the gravity field that would be measured if the effects of near-surface deviations from crustal homogeneity, produced by rift basins and other high order effects, were removed from the observed gravity. Once extracted, this field can be modeled in terms of deep crustal mantle structure and perhaps related to the structure of the rift basins. Subtraction of the regional field from the Bouguer gravity produced the residual field used in modeling the rift basins.

The regional gravity field was evaluated and constrained using several sources of information. Mathematical approaches to anomaly separation that were applied to the Bouguer gravity data included polynomial fitting, upward continuation, and spectral analysis combined with bandpass filtering. Geological constraints were imposed on the regional selection by using Bouguer values over areas of shallow basement or basement outcrop. In such areas the regional field will closely approximate the total Bouguer gravity field, differing only by a small amount that accounts for the thin sediment cover. An extensive data base of water-well logs, acquired by Marathon International Oil Company, provided values of sediment thickness in areas of shallow basement. Calibration of the regional field over each of the basinal areas was done by gravity modeling of seismic sections that traverse the gravity profile. Subtracting the gravitational effects calculated for these models from the Bouguer gravity yielded a regional field value over the basinal areas. Due to the length of the profile, the background gravity field was assessed in terms of first- and second-order surfaces rather than using a single constant value.

ANALYTICAL METHODS

Direct analytical approaches alone proved to be ineffective in extracting a proper regional gravity field. This can be attributed to two main causes. First, the Bouguer gravity profile contains a large percentage of anomalous responses from rift structures; thus, methods that rely upon statistical sampling, such as polynomial fitting, are heavily weighted by the anomalous values. As a result, high-order polynomial fitting produces a smooth curve that mimics the Bouguer gravity. Second, filtering techniques designed to produce smooth, broad, wavelength responses representative of a regional gravity field by removing high frequency responses, such as bandpass filtering and upward continuation, tended to either mimic the Bouguer gravity or average through the anomalous features, depending upon the severity of the filter. This result can be explained by the fact that the rift basins have widths of approximately the same magnitude as the distances between the basins. Filters designed to remove the anomalous lows produced by the rift basins also remove the response between basins, resulting in a profile that averages through the Bouguer curve. Reducing the severity of the filters produces a smoothed profile that mimics the Bouguer gravity.

As there is no justification to assume a positive correlation between the gravity lows and the regional gravity field over basinal areas, a regional field that mimics the Bouguer curve is not warranted on analytic approaches alone.

GEOLOGIC AND SEISMIC CONSTRAINTS

Additional constraints obtained from geologic and seismic data provided a method to calibrate the regional gravity field in various locations along the profile. Figure 9 shows sections of the profile that traverse regions of shallow basement and the intersection points where seismic lines crossed the profile. The regional field to be extracted is in theory the field that would be observed if all the near-surface features producing residual highs and lows were replaced by a homogeneous crust. For this reason the regional gravity field will approximate the Bouguer gravity in regions of shallow basement, assuming basement to be of uniform density. Deviations from crustal homogeneity can be partially accounted for by attributing the gravitational effects of high frequency variations in crustal density to the residual gravity field. Low-order change, such as gradual density increases with depth, can be accounted for by equating their effects to the background gravity field that is removed from the regional field prior to modeling. Figure 10 illustrates seventh- and eighth-order polynomial fits to the Bouguer gravity using only those control points from regions of shallow basement. The data points used were adjusted to account for the residual effect of the thin sediment cover. One section of shallow basement, between km 480 and 510, was excluded from the control points as this region is associated with a large circular residual high, delineated by both gravity and magnetics. Additional control was provided in basinal areas by gravity modeling seismic sections that traverse the profile (fig. 10). The seismic lines used ran approximately parallel to the profile and normal to the rift basins, allowing two-dimensional modeling. The residual effect of the basin fill was calculated and subtracted from the Bouguer gravity to yield regional control points. The curves generated by polynomial fitting showed good agreement with these calibration points with one exception. Gravity modeling in the Khartoum basin indicated that a residual field of approximately 29 mgal is required to account for the basin fill. The polynomial curves in figure 10 provide only a 2–7 mgal residual for the Khartoum basin. This apparent discrepancy results from the lack of shallow basement control in the central region of the profile (see fig. 9). The basement control on both flanks of the central region yields a downward slope in the polynomial curves toward the Khartoum basin, producing an uncalibrated low over the basin. To accommodate the approximately 29 mgal residual requires that a high in the regional field must occur over the basin.

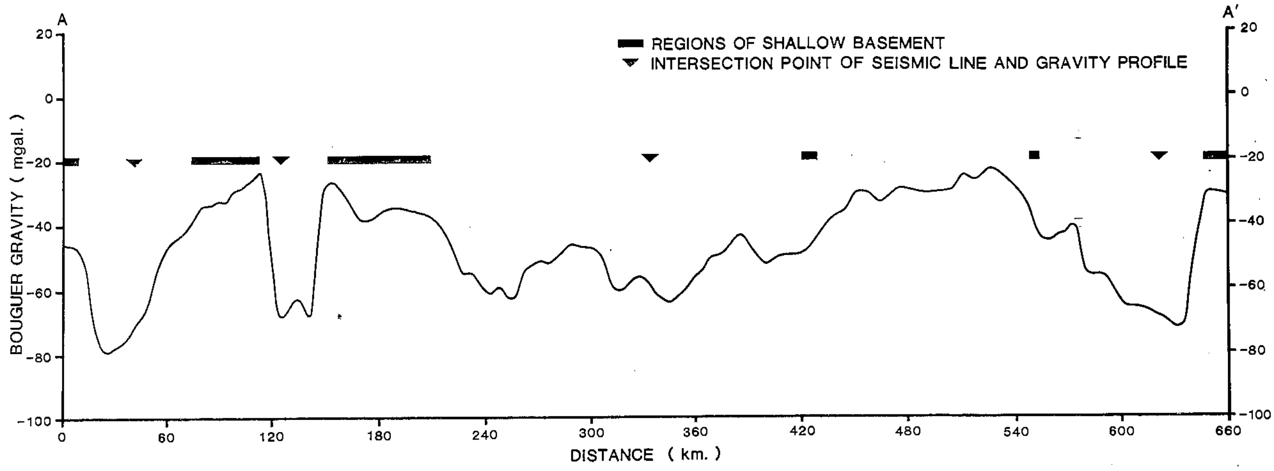

FIGURE 9.—*Bouguer gravity along profile A-A′ showing regions of shallow basement traversed by the profile and points where the profile intersects seismic lines used to calibrate the regional gravity field. The regions of shallow basement were determined using both water-well data and the geologic map of Sudan.*

BACKGROUND GRAVITY

Profile A-A′, as seen on figures 7 and 8, lies on the eastern flank of, and approximately normal to, the "lesser Bouguer anomaly" of Africa (Brown and others 1980). The anomaly, which has been equated to deep lithospheric-asthenospheric structure (Bermingham and others 1983, Brown and Girdler 1980, Brown and others 1980, Crough 1981, Fairhead 1979, Girdler 1975), provides information about the nature of the background gravity field. The position of the profile with respect to the "lesser Bouguer anomaly," together with its length, suggest that the background field in the study area should be a low-order surface increasing gently to the northeast. This trend is also indicated from the results of a north African gravity traverse that crossed through northern Sudan (Brown and Girdler 1980). All analytic approaches, including low-order polynomial fitting and high-cut bandpass filtering, confirmed a gentle first-order rise in the background field from A to A′.

GRAVITY ANOMALIES

Figure 11 illustrates the final profiles for the regional and background gravity fields, based on all data sources. The background field selected is a first-order surface rising from −43.8 to −36.8 mgal along profile A-A′ while the regional field ranges from −43.2 to −21.7 mgal. Subtraction of the background field from the regional gravity produces the curve used to model deep crustal structure.

REGIONAL GRAVITY MODEL

The most striking correlation seen on figure 11 between the Bouguer and regional gravity are the highs that occur in the regional gravity field over the basins. One central high with a magnitude of 21 mgal above background is situated over the Bara and Kosti basins. Highs with magnitudes of approximately 5 and 9 mgal occur over the Khartoum and Atbara basins, respectively. Highs in the regional gravity field over basinal areas is a characteristic observed in many of the rifts of the Central African Rift System (Adighije 1981, Browne and Fairhead 1983, Browne and others 1985, Fairhead unpubl. manu.). The wavelength of the highs and positive values of the regional field indicate a deep source and positive density contrast for the causative body. One geologic model that can successfully explain the observed regional gravity field consists of a uniform crustal slab thinned under regions of rifting with a corresponding rise in the upper mantle. The density contrast across the crust–upper mantle boundary typically ranges between 0.40 to 0.60 g/cm^3 (Bott 1982, Woollard 1966). Figure 12 illustrates the proposed geologic model along with the observed and calculated regional gravity field resulting from two-dimensional inverse modeling of the regional gravity. The calculated field is based upon a crust–upper mantle density contrast of 0.5 g/cm^3 and an assumed initial crustal thickness of 30 km. Using these parameters, crustal thinning reached a

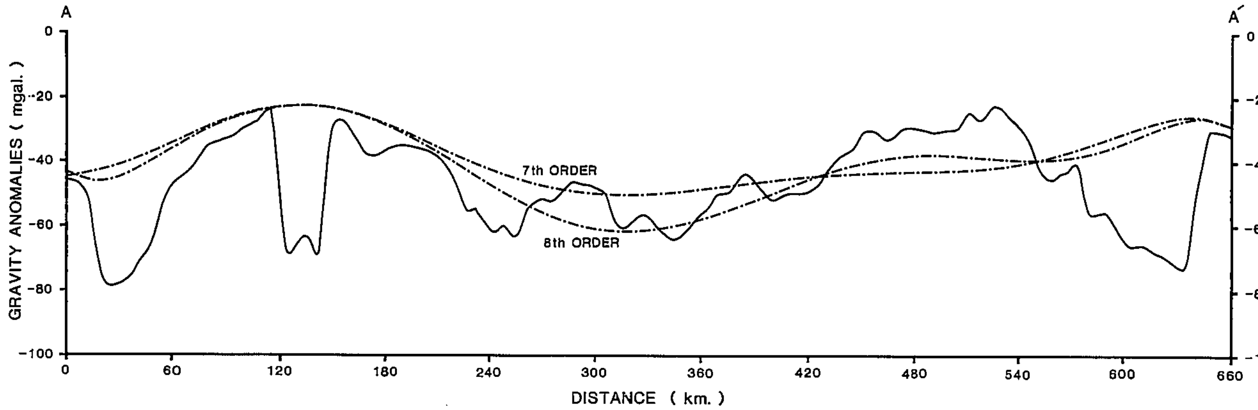

FIGURE 10.—*Bouguer gravity along profile A-A' with seventh- and eighth-order polynomial fits to the Bouguer gravity field using only those values from regions of shallow basement for control points. The Bouguer values from these areas were adjusted to account for the amount of sediment cover prior to polynomial fitting.*

maximum of approximately 2.0, 0.5, and 1.0 km beneath the White Nile, Blue Nile, and Atbara Rifts, respectively.

Due to uncertainty in the values of the independent variables (crustal thickness and crust-mantle density contrast) involved in calculating the model, the solution is non-unique. Figure 12 does, however, provide a schematic, plausible model of the crust-mantle structure, with the degree of crustal thinning varying in accordance with changes made to these variables.

One method of constraining the variables of initial crustal thickness and crust-mantle density contrast is by comparing the amount of crustal extension calculated from the regional gravity model with the amount of extension observed on seismic sections. The method used in making this comparison is outlined below.

CRUSTAL EXTENSION CALCULATIONS

The proposed tectonic model responsible for generating areas of thinned crust involves lithospheric stretching that results from tensional stresses acting normal to the axes of the rift basins. Such a model provides a mechanism for rift basin formation through isostatic and thermal subsidence (Jarvis 1984, Jarvis and McKenzie 1980, McKenzie 1978). This model is discussed in more detail in the section on rifting mechanism.

Calculation of the amount of crustal extension can be made using the regional gravity model (fig. 12). By combining the cross-sectional area of the rift basins with that of the upper mantle swell and assuming conservation of the crust, the magnitude of extension can be calculated as shown schematically in figure 13. The general lack of volcanism in the rift basins, as determined by seismic data, lends strength to the assumption of crustal conservation. Seismic sections provided the means for measuring the cross-sectional areas for each of the basins. Cross-sectional areas of approximately 70.0, 71.0, 50.0, and 75.0 km^2 were determined for the Bara, Kosti, Khartoum (including the Khartoum South), and Atbara Basins, respectively. Combining this area with that of the upraised mantle, calculated from a regional gravity model, yields the total induced area and crustal extension. The area of the upraised mantle, and hence the total induced area, varies in accordance with changes made in the variables used to calculate a regional gravity model. A second method of measuring crustal extension is also available using the seismic data. A strong basement reflection is a consistent characteristic of seismic data acquired in each of the major basins. Extension within each basin was determined by taking the difference between the distances separating basin edges and the sum of the lengths of basement reflectors within the basins.

A series of regional gravity models was generated using numerous possible combinations of crust-mantle density contrasts ranging from 0.35 to 0.65 g/cm^3 in increments of 0.05 g/cm^3, and initial crustal thicknesses ranging from 20 to 45 km in increments of 5 km. Automatic structural inversion using fast Fourier transforms was used in generating the models. The magnitude of extension was calculated from each model and compared with the amount of extension observed from the seismic records, thereby providing limiting ranges on the non-unique parameters used in generating the regional gravity model.

Figure 14 illustrates the resulting amounts of extension as a function of both the density contrast and crustal thickness. The shaded region shows the range of extension calculated from seismic data. This range is the cumu-

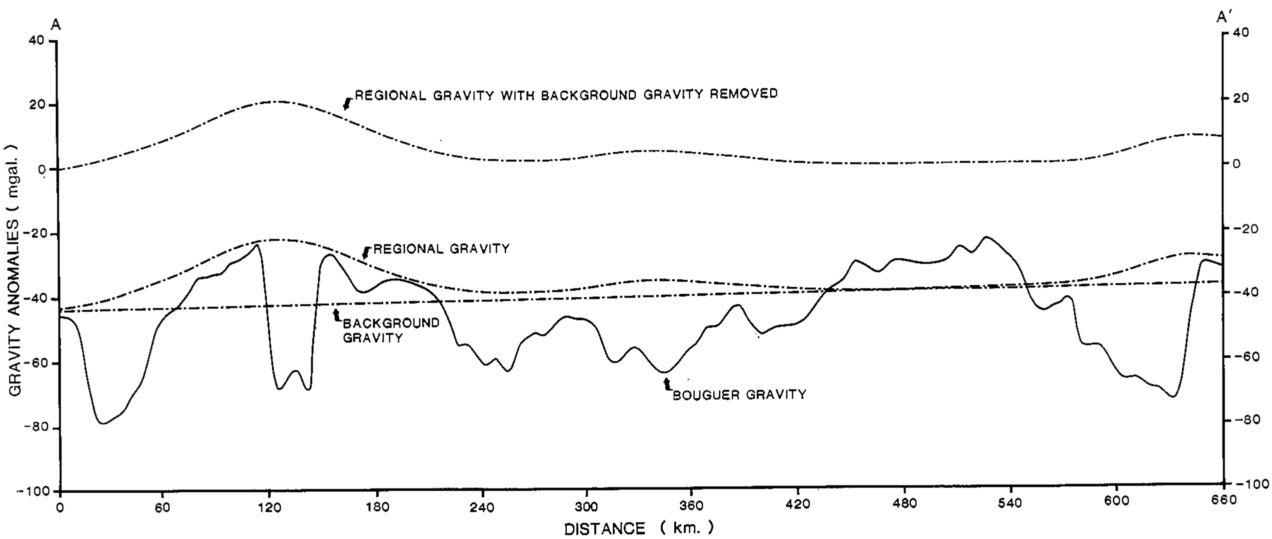

FIGURE 11.—*Bouguer gravity, regional gravity, background gravity, and regional gravity with background gravity removed along profile A-A'.*

lative amount of extension, approximately 12 to 14 km, along profile A-A'. Quantities for each basinal area are 3.0 to 3.5 km for the Bara Basin, 4.0 to 4.5 km for the Kosti Basin, 2.0 to 2.5 km for the Khartoum and Khartoum South Basin, and 3.0 to 3.5 km for the Atbara Basin.

The constraints placed upon the parameters of crustal thickness and crust–upper mantle density contrast by this procedure are evident from figure 14. Assuming, for example, a density contrast of 0.50 g/cm^3, a crustal thickness of 32 to 37 km is required. Crustal thicknesses less than 25 and greater than 45 are not in agreement with extension based on seismic calculations regardless of the density contrast used. Brown and others (1980) determined a depth of 36.2 km for the Mohorovicic discontinuity for a standard African lithosphere using the AFRIC model of Gumper and Pomeroy (1970), which was developed using group and phase velocity dispersion data. This agrees well with the crustal thickness predicted above, using a crust–upper mantle density contrast of between 0.40–0.50 g/cm^3.

Browne and Fairhead (1983) calculated crustal extension of between 22 and 45 km in the Abu-Gabra Basin of the Southern Sudan rift using regional gravity models. These figures compared with the amount of extension observed here in central Sudan indicate a general decrease in the magnitude of crustal extension from the southwest to the northeast away from the major zone of lithospheric thinning located along the western border of Sudan (see fig. 8).

RESIDUAL GRAVITY MODELS

The residual gravity field (fig. 15), obtained by removing the regional from the Bouguer gravity (see fig. 11), was used to model the major rift basins. Residual values range from −47.2 to 15.2 mgal. Two-dimensional forward modeling was performed in three segments along profile A-A'. The first segment extends from km 0 to 209, covering the Bara and Kosti Basins of the White Nile Rift. The second segment extends from km 209 to 433, covering the Khartoum South and Khartoum Basins of the Blue Nile Rift. The third segment extends from km 550 to 660, covering the Atbara Rift.

Densities used in the modeling procedure for the intrabasin sediments were derived from Gardner's formula (Gardner and others 1974) using interval velocities obtained from the stacking velocities used in processing the seismic data (Dix 1955). Within each basin the degree to which separate density bodies were differentiated was largely a function of the seismic character of the basin. In the residual gravity models that follow it can be seen that the Bara Basin has been differentiated into more density bodies than the other basins. Seismic sections in the Bara Basin show a considerable number of continuous reflectors within the intrabasinal fill, whereas the Kosti, Khartoum South, and Atbara Basins show a relatively, seismically transparent sedimentary section. Due to this transparent nature, a single density body was used for a large portion of the basin fill; this, however, is not intended to

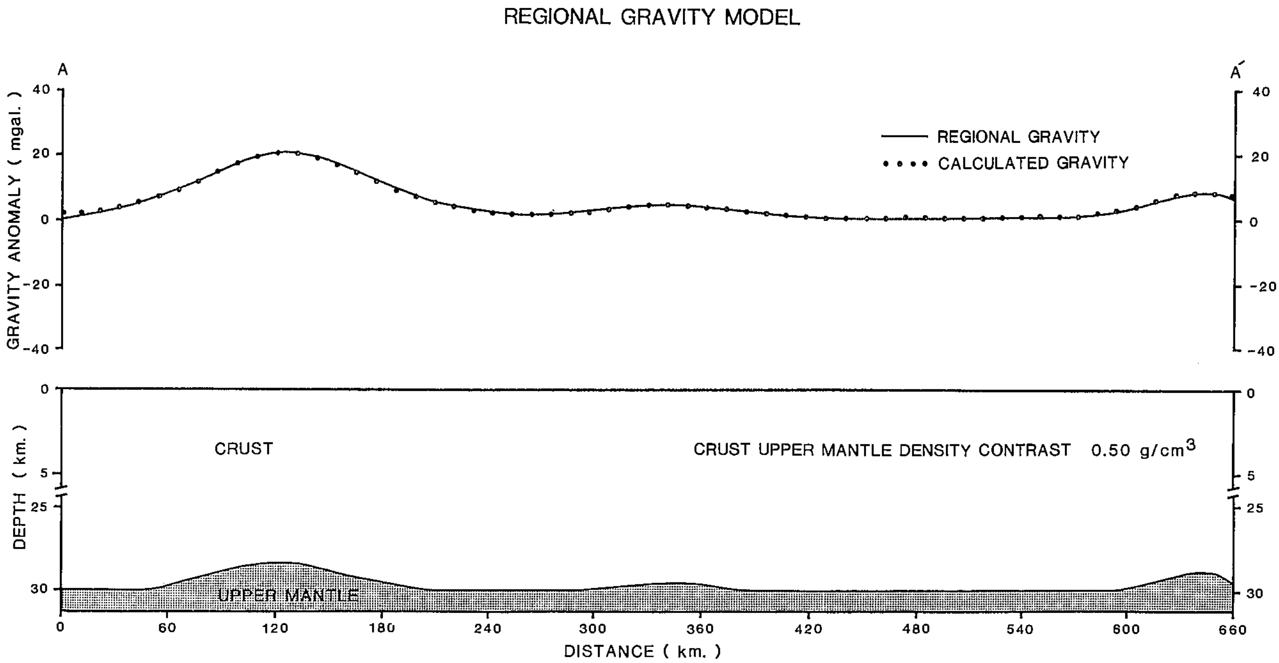

FIGURE 12.—*Regional gravity model along profile A-A'. The model assumes an unthinned crustal thickness of 30 km and a crust–upper mantle density contrast of 0.5 g/cm^3.*

imply homogeneity in basin-fill lithology. Density contrasts used in model calculations were obtained by subtracting a background crustal density of 2.7 g/cm^3 from the basin-fill values given below.

WHITE NILE RIFT

The residual gravity model for the White Nile Rift is illustrated in figure 16. Density values used range from 2.1 to 2.49 g/cm^3 for the Bara Basin and 2.1 to 2.37 g/cm^3 for the Kosti Basin. The minimum residual gravity lows for the Bara and Kosti Basins are −38.4 and −47.3 mgal, respectively.

The Bara Basin section of the model possesses a half-graben geometry with a major bounding fault on the southern side. Modeling yields a maximum depth of approximately 2950 m and a width of 45 km.

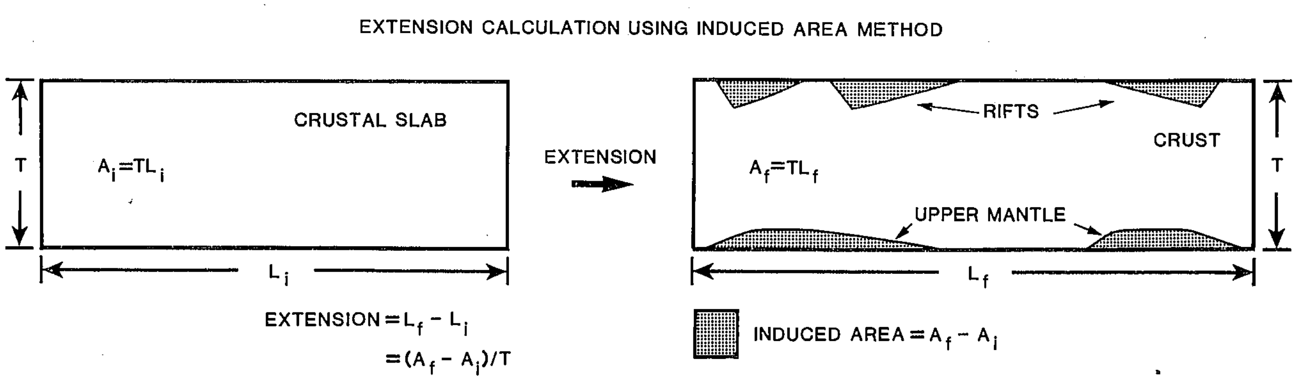

FIGURE 13.—*Schematic illustrating the method used in calculating the amount of crustal extension from a regional gravity model. The method assumes conservation of crust. The cross-sectional area of the rift basins was determined from seismic sections, the area of crustal thinning is determined from regional gravity models.*

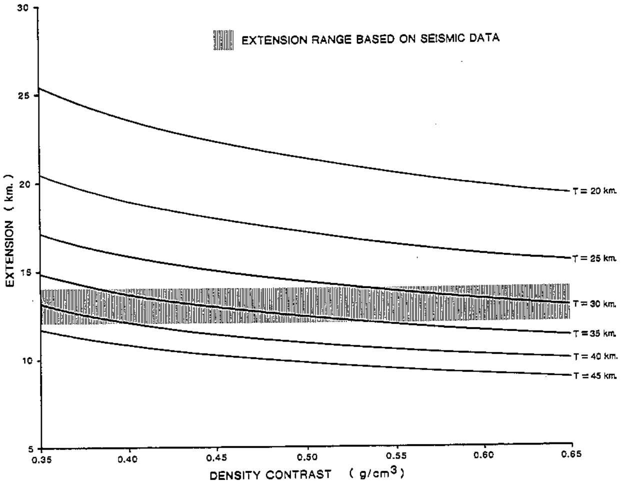

FIGURE 14.—*Graph showing the amount of crustal extension, based on the method of calculation shown in figure 13, using a series of regional gravity models generated using various combinations of crust-mantle density contrasts and crustal thicknesses (T). The different solutions are compared with the cumulative amount of extension observed on seismic sections in the rift basins along profile A-A'. (For a crust-mantle density contrast of 0.50 g/cm^3 and a crustal thickness of 35 km, the amount of extension is approximately 12.5 km.)*

The Kosti section of the model shows an apparent full-graben geometry for this basin with steeper bounding faults than the Bara Basin. A large internal structural high is indicated by a central arc of approximately 6.5 mgal in the residual gravity profile. Modeling suggests a maximum basin depth of approximately 4200 m, rising to approximately 2600 m over the internal high, and a width of approximately 32 km.

The material with a density of 2.1 g/cm^3 extending across the White Nile Rift is a postrift sediment sequence that thickens over basins and thins over rift flanks. As discussed later, this pattern of sedimentation has implications for the proposed mechanism of rifting.

BLUE NILE RIFT

The residual gravity model for the Blue Nile Rift is illustrated in figure 17. Density values for the basin fill range from 2.20 to 2.40 g/cm^3 in both the Khartoum South and Khartoum Basins. Minimum residual gravity lows are −23.9 and −28.9 mgal for the Khartoum South and Khartoum Basins, respectively.

The model produces half-graben geometries for both of the major basins with a major bounding fault on the north side of the Khartoum South Basin and on the south side of the Khartoum Basin. Maximum depths of approximately 1550 m for the Khartoum South Basin and 1950 m for the Khartoum Basin are indicated by the model.

It should be noted that even with the acquisition of gravity and seismic data throughout the Blue Nile Rift area, there still exist uncertainties in some of the structural trends and fault patterns, although the overall NW–SE pattern is still evident. This lack of detailed delineation is in part due to the thick postrift sediment sequence that blankets the entire Blue Nile Rift. Postrift sediment cover has been observed over all the basins under study but is much thicker in the Blue Nile Rift, reaching a maximum thickness of approximately 910 m over the Khartoum Basin. This sediment sequence is thickest between the White Nile and Blue Nile Rivers. The increased depth of burial of the rift structures beneath the postrift sediments in this region causes an inherent decrease in the resolution of the gravity data.

Although the geologic map of Sudan (Geological and Mineral Resources Department, Khartoum, 1981) shows

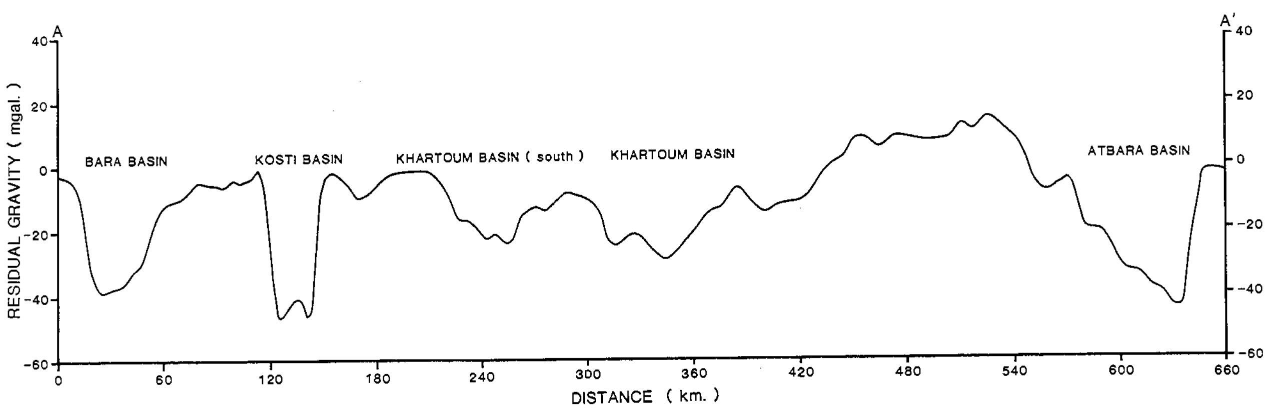

FIGURE 15.—*Residual gravity field along profile A-A'. Residual values range from −47.2 to 15.2 mgal.*

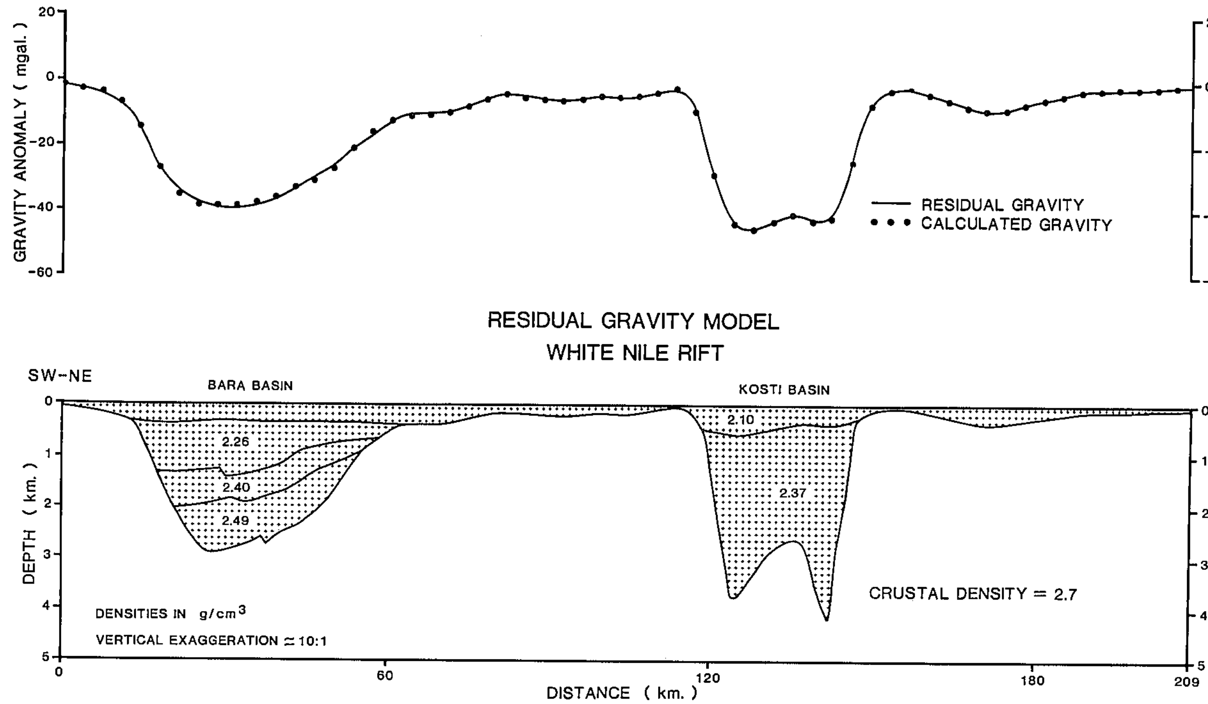

FIGURE 16.—*Residual gravity model of the White Nile Rift (km 0–209 along profile A-A ').*

the surface sediments over the Blue Nile Rift to be Tertiary-Quaternary rocks of the Umm Ruwaba and Geriza Formations, samples taken from shallow boreholes indicate that the bulk of the postrift sediment package consists of the Nubian Sandstone Formation (Aboul Ela and Mabrouk 1978, Omer 1975, 1983). Palynological studies by Aboul Ela and Mabrouk (1978) showed the Nubian Sandstone in this region to be Upper Cretaceous in age (Santonian-Campanian) with deposition occurring in a shallow water, nonmarine environment. Omer (1975), in studying the sedimentation patterns of the Nubian formation and paleocurrents throughout the Khartoum province, determined that deposition occurred in a NW–SE-trending zone of subsidence along the trend of the Blue Nile Rift.

ATBARA RIFT

The residual gravity model of the Atbara Rift is illustrated in figure 18. Density values range from 2.1 to 2.33 g/cm^3. A minimum residual gravity low of −44.2 mgal is observed over the basin.

The model shows half-graben geometry with the major bounding fault on the northern side of the basin. The apparent position of the main rift-bounding fault corresponds with the position of the Atbara River, suggesting possible fault control for the river's course. Slope breaks observed in the gravity profile and the model indicate that a series of normal faults occurs between km 570 and 630 and that the normal faults are downdropped to the northeast. These are likely major antithetic faults dipping toward the major bounding fault.

A maximum depth of approximately 3100 m and a width of 65 km is indicated by the model.

DISCUSSION

RIFT GEOMETRIES

Several observations made from the gravity data covering the entire study area and from seismic sections covering the basins are introduced here since they play a major role in the understanding of both the rift geometries, as demonstrated by the residual gravity models, and the mechanisms believed responsible for generating the rifts.

First, both gravity and seismic data demonstrate that asymmetric half-graben geometry is the dominant large-scale structural configuration of the rift basins. Second, the gravity and seismic data illustrate that most of the major rift basins are actually composed of a series of individual sub-basins, typically 30–50 km in length, each having one main bounding fault, a pattern consistent with half-graben geometry. Third, the main bounding faults of the sub-basins have various amounts of curvature, in plan view, toward the hanging wall. Fourth, seismic data reveal that the dip on the main bounding faults and on the

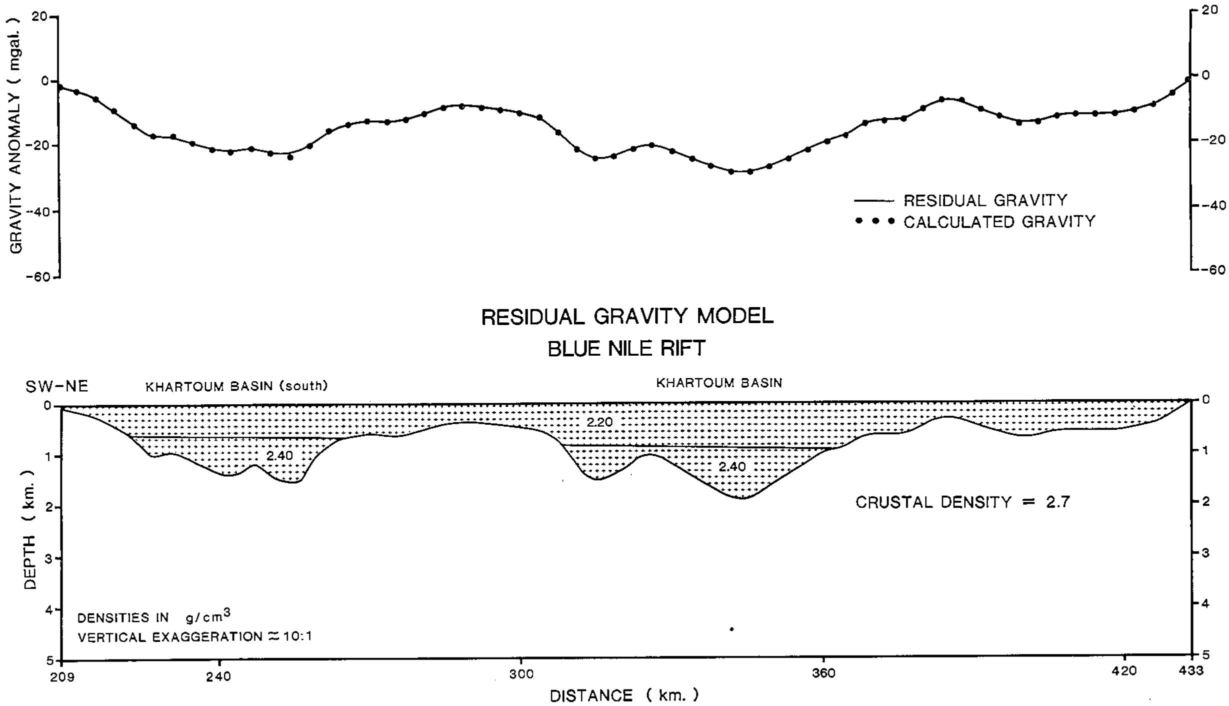

FIGURE 17.—*Residual gravity model of the Blue Nile Rift (km 209–433 along profile A-A').*

major internal synthetic and antithetic faults decreases with depth, producing a listric pattern. Fifth, the individual sub-basins are commonly separated by a complex zone of faulting forming an internal structural high along the rift axis between sub-basins. And sixth, the main bounding fault often reverses to the opposite side of the rift (along the rift axis in plan view) between individual sub-basins; this combined with the plan-view curvature gives a cuspate flip-flopping appearance to the main bounding fault along the length of the rift axis.

A useful tool in outlining many of these geometries is the calculation of the horizontal derivative of the gravity field in both plan view and along profiles. Figure 19 illustrates the horizontal derivative of the residual gravity field along profile A-A'. Response from the major bounding faults is seen as the spikes along the profile. The relative amplitudes for a given basin give an indication of the rift asymmetry, and relative amplitudes between basins give a relative measure of the dip and amount of displacement along the main bounding faults—with one exception. The weak response from the major faults of the Blue Nile Rift is again related to the thick postrift sediment cover blanketing the individual sub-basins causing a decrease in the gradients of the gravity field. The response from the Bara Basin indicates half-graben geometry with the major bounding fault on the southern side, and the response from the Atbara Basin indicates the same geometry with the major bounding fault on the northern side. The response from the Kosti Basin indicates greater dip on its main bounding faults. The approximately equal amplitudes would also tend to imply an atypical full-graben geometry for this basin. As discussed later, however, this appearance can be adequately explained due to the reversal of the main bounding fault to the opposite side of the rift, between individual sub-basins.

Similiar rift geometries have been reported from studies of other rift basins in east and north Africa (Bosworth 1985a, Derksen and others 1984, Moustafa 1976, Reynolds and Rosendahl 1984, Rosendahl and others in press). The region between adjacent sub-basins where reversal of the main bounding fault to the opposite side of the rift commonly occurs was first termed a "hinge zone" by Moustafa (1976) from a study of the Gulf of Suez Rift. Moustafa divided the Gulf of Suez, along the rift axis, into three tectonic sections, referred to as "dip provinces" based on contrasting regional dip attitudes on the interior fault blocks. The regional dip of the fault blocks within each province was shown to be toward the major NW–SE-trending border faults of the rift. The three dip provinces are the northern West Araba province with SW dips on the internal fault blocks, the central Belayim province with NE dips, and the southern Amal province having SW dips. The opposing dips of fault blocks be-

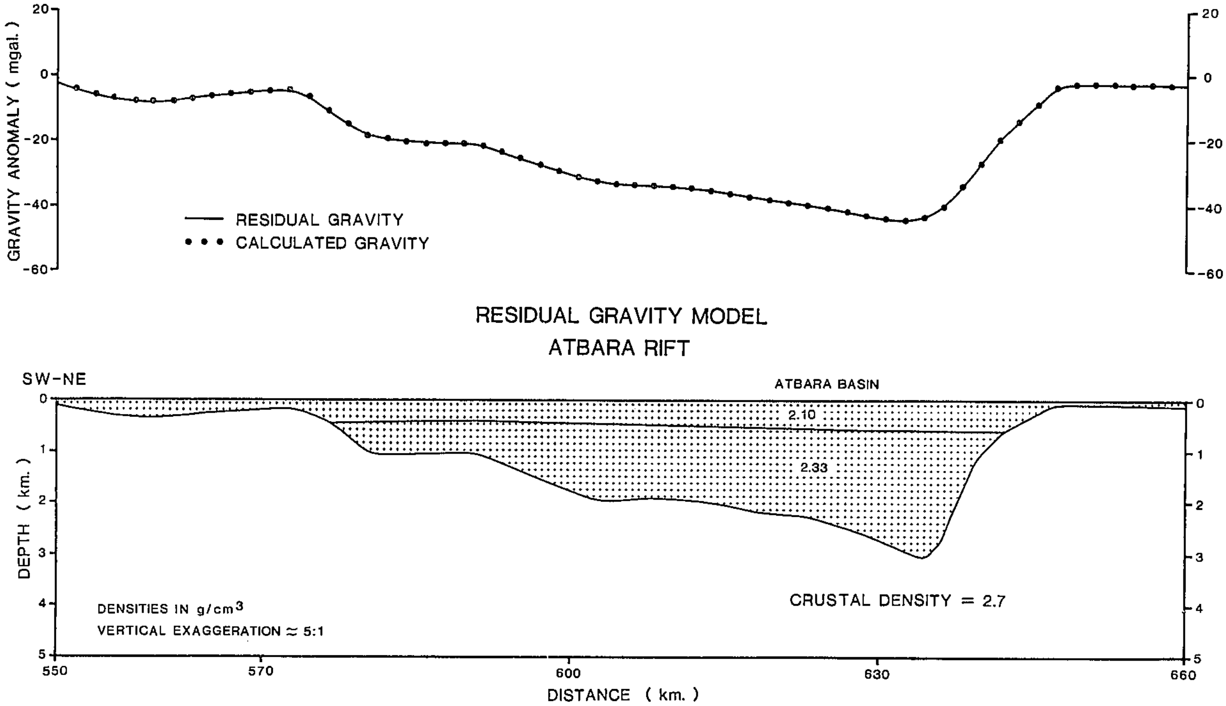

FIGURE 18.—*Residual gravity model of the Atbara Rift (km 550–660 along profile A-A').*

tween adjacent provinces show that rotational movement occurred along hinge faults separating the provinces. Two NE–SW-trending hinge zones separating the West Araba province from the Belayim province, and the Belayim province from the Amal province were noted by Moustafa (1976). Reynolds and Rosendahl (1984) and Rosendahl and others (in press) have reported results from seismic reflection studies in the Tanganyika rift lake of east Africa. These workers noted that the fundamental building block of the rift are half-graben sub-basins usually separated by a complex zone of faulting that forms an interbasinal ridge trending oblique to the rift axis. The main bounding faults of sub-basins are arcuate in plan view, often alternate to opposite side of the rift between adjacent sub-basins, and interconnect through the interbasinal ridges, giving a sinusoidal appearance to the main faults in map view. A consequence of the arcuate shape of the main bounding fault in plan view is that the fault must also be arcuate or listric in cross section. Full-graben forms usually resulted from lines of observation that traversed over an interbasinal ridge and encountered the main bounding faults of two adjacent half-grabens. Seismic lines with this orientation also showed various forms of axial highs corresponding to the interbasinal ridges. Rosendahl and co-workers concluded that the interbasinal ridges at the ends of sub-basin units would be zones of rotational and shear motion.

The asymmetry of continental rifts in cross section and the accommodation of crustal extension through low-angle normal listric faulting has been recognized by several workers using geological and geophysical data (Bally and others 1981, Evison 1959, Hamblin 1965, Harding and Lowell 1979, Wernicke 1981, Wernicke and Burchfiel 1982). The listric nature of the faults bounding major rifts indicates that they probably change into essentially planar detachments with increased depth (Wernicke 1981).

Many of these geometric observations can be explained from concepts of rift fault development introduced by Bosworth (1985a) from his analysis of several rift basins throughout northeast Africa. He proposed that the rift asymmetry develops as a consequence of competing low-angle listric detachments. Figure 20 illustrates the main concepts involved in the model for the evolution of continental rifts. Upon rift inception, opposing faults begin to develop into a listric system. As rifting advances, the two low-angle detachment systems work in opposition so that the displacement of one dominates and locks the opposite fault (locked detachment of fig. 20). With continued rifting, subsidence and extension continue along the active border fault, resulting in half-graben formation. The arcuate nature of the main bounding fault in plan view also imposes limitations on the dimensions of developing rift sub-basins. Changes in the dominating low-angle detachment for adjacent half-graben sub-basins would result in a

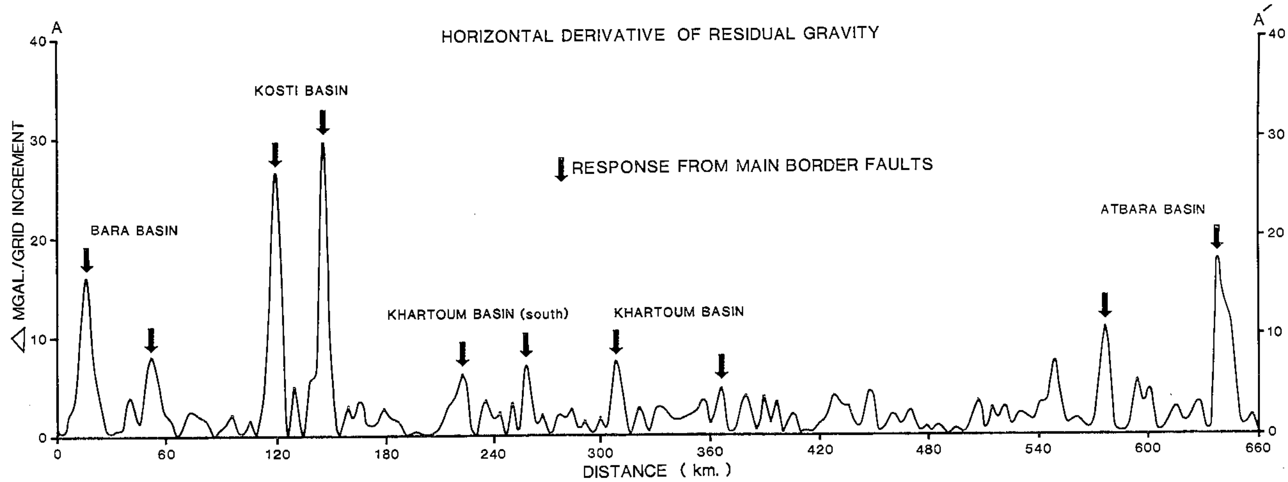

FIGURE 19.—*Horizontal derivative of the residual gravity along profile A-A'. Units are changed in milligals per grid increment where the grid increment is 4.0 km.*

reversal of the main bounding fault to the opposite side of the rift. The section of the rift between adjacent sub-basins where reversal of the main bounding fault commonly occurs is often a complex zone of faulting, referred to as an accommodation zone (Derksen and others 1984). Reversal in the regional dip on the fault blocks between adjacent sub-basins in combination with the plan-view curvature of the main bounding faults suggests that the accommodation zones must be dominated by shear and rotational faulting. Figure 21 illustrates plan view observations of these geometries. The reversal of the main bounding fault, in plan view, is evident on figures 20 and 21.

This listric fault model allows for possible near-horizontal floors on fault blocks within rifts. Delineation of horizontal reflectors on seismic sections, interpreted as indicating little or no rotation on rifted fault blocks, has been used to argue against listric faulting in some rift environments (for example, see Brown and others 1980). In the Kosti Basin, seismic data has shown the dominance of listric faulting throughout the basin; however, some of the seismic lines have shown a near horizontal basement reflector. These could result from the net effects of competing rotations on opposing listric faults. This type of development would require the recutting of the deep crustal section below the zone where opposing listric systems merge, due to the offsetting displacements along the faults. The mechanical viability of this process may be related to the depth at which merging of the fault systems occurs. Should the dip along the listric system produce merging in an area of crustal weakness, such as the brittle-ductile transition zone, a locked detachment may not develop. This would allow offsetting rotations in the overlying fault block to produce near horizontal basement reflectors. Horizontal reflections observed on seismic sections could also result if the seismic line were recorded along the strike of an accommodation zone separating rift sub-basins.

The dip provinces and hinge zones proposed by Moustafa (1976) and the half-grabens separated by inter-basinal ridges noted by Reynolds and Rosendahl (1984) and Rosendahl and others (in press) would correspond to the sub-basins and accommodation zones of the model of Bosworth (1985a).

Using the concepts of reversal in the main bounding fault to opposite side of the rift between adjacent sub-basins and oblique angles of accommodation zones, the apparent full-graben geometry of the Kosti Basin can be explained as demonstrated by the schematic of figure 22. Profile A-A' crosses the Kosti Basin along a path that traverses both the main boundary faults of adjacent half-graben sub-basins and an accommodation zone. This results in a full-graben appearance with an internal structural high as seen on the Kosti Basin residual gravity model.

Rift basin cross-section balancing techniques presented by Bosworth (1985b) show that the depth to detachment of the listric bounding faults lies between 12–19 km for the rift basins in central Sudan. This indicates that the detachment may occur along the brittle-ductile transition zone (Montadert and others 1979) (see fig. 20).

RIFTING MECHANISM

Mechanisms for passive rift evolution introduced by McKenzie (1978), Jarvis and McKenzie (1980), and Jarvis (1984) adequately explain the results of the regional and

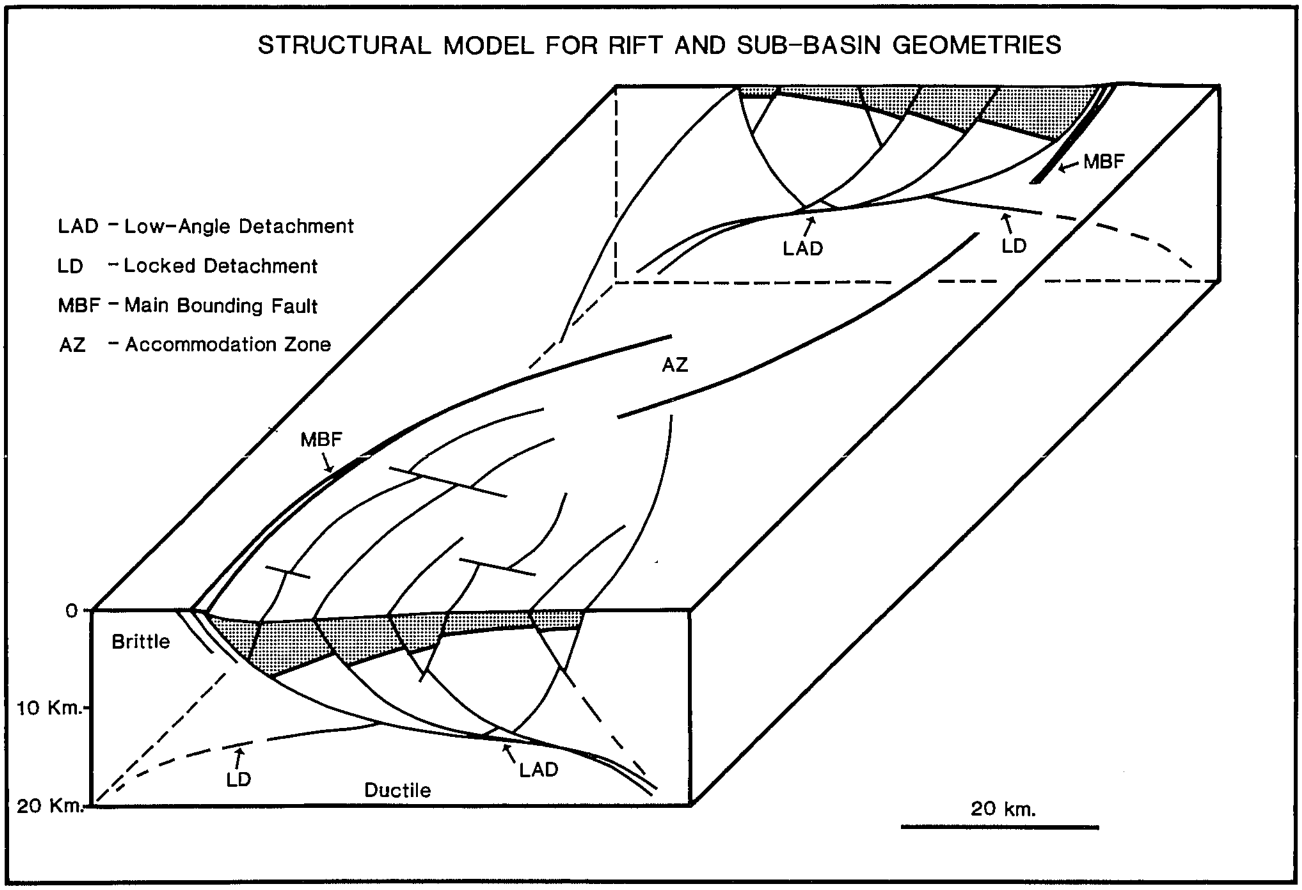

FIGURE 20.—*Block diagram of rift and sub-basin geometries (after Bosworth 1985a). The model proposes that rift asymmetry develops as a consequence of competing listric fault systems. Upon rift inception the bounding faults begin development into opposing listric faults. For full-graben geometry to develop, repeated cutting of the deeper crustal section must occur. Should displacement on one of the main listric systems dominate, the opposing system may lock, leading to the development of half-graben geometry with continued rift evolution. Curvature of the main bounding fault in plan view imposes limitations on the lengths of developing sub-basins. The main bounding fault often reverses to the opposite side of the rift between adjacent sub-basins along zones of complex faulting referred to as accommodation zones.*

residual gravity models. Rift development is a result of the mechanical, isostatic, and thermal responses to crustal extension and lithospheric thinning produced by regional tensile stresses.

Crustal thinning, caused by horizontal extension, is accommodated by brittle rupture in the upper crust and passive upwelling of the lower crust and upper mantle, below the brittle-ductile transition zone. Brittle rupture in the upper crust produces listric faults that bound the rift basins.

It was demonstrated by McKenzie and Jarvis that the isostatic response to thinning the continental crust could be variable subsidence, the magnitude dictated by initial crustal thickness. The thermal effect on the direction of epeirogenic movement varies during the rifting process. During the stretching phase thermal uplift in the upper crust occurs because of the rise in isotherms produced by the upraised lower crust and upper mantle. However, as the model does not directly utilize a deep-seated mantle diapir as the driving mechanism, an anomalous heat source is not available. Any heating and expansion in the upper crust can only occur at the expense of cooling and contraction in the lower stretched zone. After cessation of stretching, cooling in the upraised lower crust and upper mantle results in a net thermal subsidence. Upon rift inception the initial epeirogenic movement is the result of the competing motions of isostatic subsidence and thermal uplift while the long period movement is general subsidence.

Considering the effects of the horizontal component of two-dimensional heat flow in regions of thinned crust, Jarvis (1984) concluded that subsidence would advance more rapidly for a narrow graben than a wide graben and that temporary uplift along the flanks of the graben would

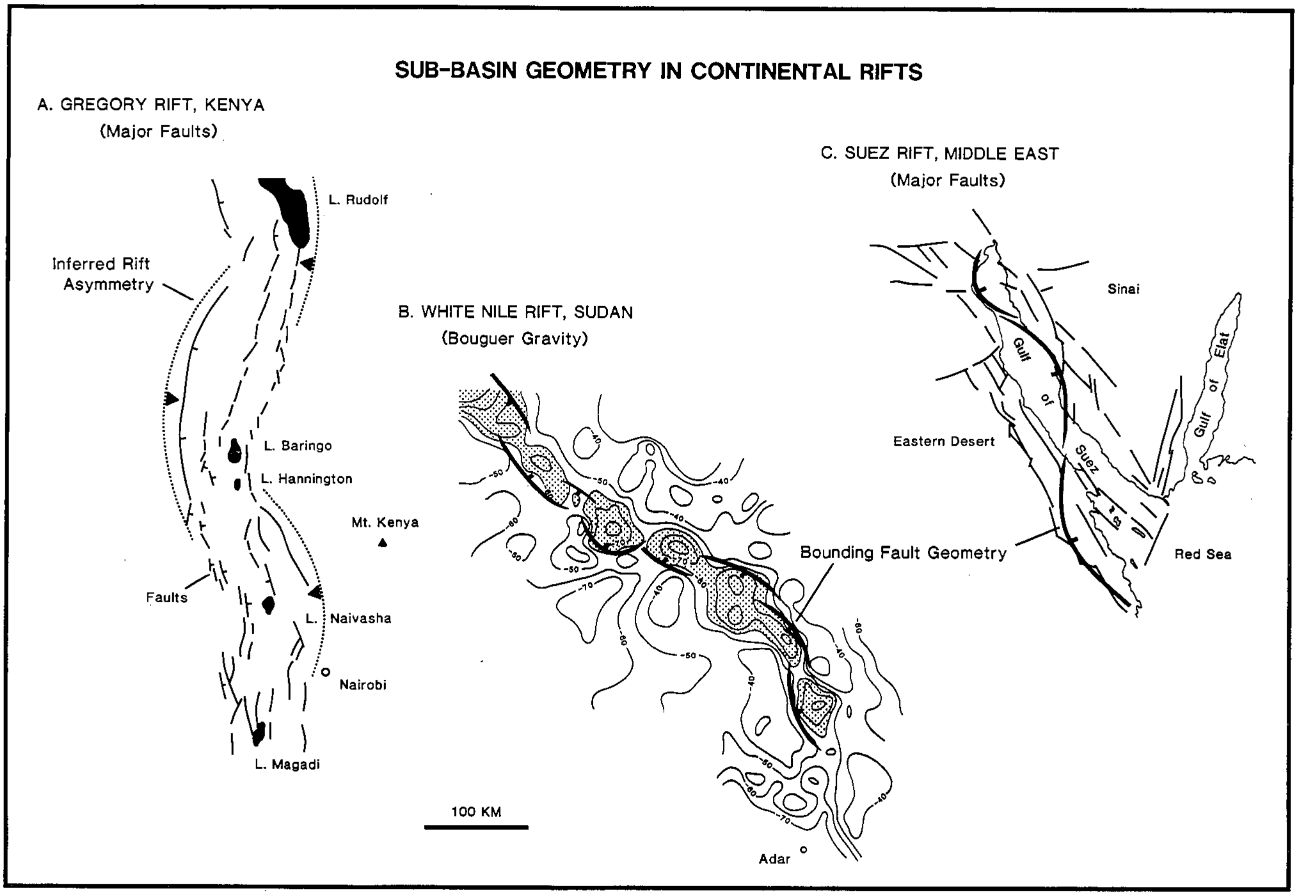

FIGURE 21.—*Examples of plan view geometries in continental rifts. Case A of the Gregory Rift is from Maguire and Long (1976), case B is gravity data covering the White Nile Rift (Bara Basin) from Browne and others (1985), case C of the Gulf of Suez Rift is from Garfunkel and Bartov (1977) and Moustafa (1976). Major fault curvature and asymmetry is noted in all cases (after Bosworth 1985a).*

result because of thermal expansion. The residual gravity model of the Kosti Basin (fig. 16) supports Jarvis' model. The postrift sediment sequence (density 2.1 g/cm^3) is thick within the rift, thin over the rift flanks, but is somewhat thicker away from the flanks (particularly evident on the northern side of the basin). Seismic data has also shown that the Kosti Basin has fewer strong, basin-wide reflective events than the wider Bara Basin, suggesting that rapid infilling of clastic material occurred in response to more rapid subsidence. This rapid subsidence of the Kosti Basin is related to its position at the apex of the maximum anomaly in the regional gravity field (see fig. 11). Modeling of this field in terms of crustal thinning and mantle uplift places the Kosti Basin at a position to be most influenced by the effects of lateral heat flow.

REGIONAL GEOLOGIC MODEL

Figure 23 illustrates a regional geologic model along profile A-A′. The scenario presented here is that the NW–SE-trending rift basins and thinned crust in central Sudan formed in a regime of NE–SW-directed extension. Brittle crustal rupture along listric faults accompanied isostatic and thermal subsidence in response to crustal thinning leading to rift formation. The listric main bounding faults change into planar detachments in the brittle-ductile transition zone. These rifts lie on the eastern flank of a major zone of lithospheric thinning (see Bouguer anomaly map of Africa, figs. 7 and 8). The genetic relationship between this zone of lithospheric thinning and the regions of crustal thinning associated with the rifts in Sudan is unclear; we can only speculate whether they were produced by the same processes or whether the zone of lithospheric thinning produced forces that led to crustal thinning and rift development. In either case, the rift basins in central Sudan provide examples of "passive" rifts as discussed by Jarvis (1984:14–15).

Crustal thinning is well established by the regional gravity field. The subsident nature of the rifts is also well documented by the positive correlation in position and

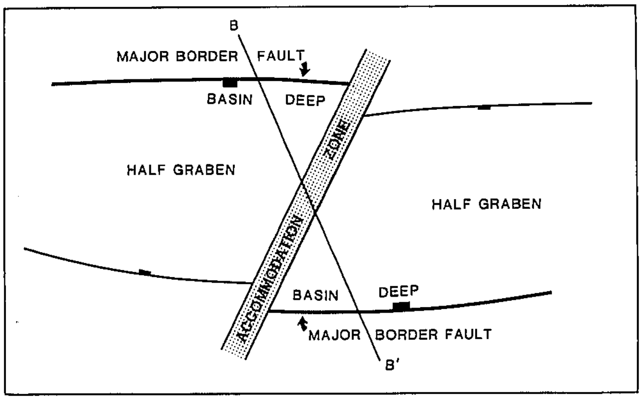

FIGURE 22.—*Plan view schematic of half-grabens with accommodation zone. In cross section, profile B-B' would have the appearance of a full-graben with an internal structural high corresponding to the accommodation zone.*

trends between the rift basins and areas of Cenozoic sedimentation (see figs. 5 and 6). This correlation is true not only for the rifts of central Sudan but also for the rifts in southern Sudan. Modeled thicknesses of the postrift sediment package also indicate the subsident nature of the rifts.

ABSOLUTE AND RELATIVE AGE OF RIFTING

The age of rifting is tentatively considered to be Cretaceous, based on (1) the reported age of basin fill of the structurally similar southern Sudan rifts (Browne and Fairhead 1983, Fairhead unpubl. manu., Nicod 1982); (2) Upper Cretaceous (Santonian-Campanian) age determinations made from palynology studies of samples from two wells, one located just north of the Kosti Basin and one over the Khartoum South Basin, in the postrift sediments (Aboul Ela and Mabrouk 1978); and (3) Upper Cretaceous (Senonian-Turonian) age dates determined using palynomorph assemblages recovered from well cuttings of a well recently completed in the Kosti Basin by the consortium of oil companies.

Relative ages of rifting of the four major rifts remains a major unanswered question but should be resolved with the planned drilling of these basins. However, under the subsidence model of rifting proposed by McKenzie (1978), Jarvis and McKenzie (1980), and Jarvis (1984) it can be speculated that the Blue Nile Rift is older than the other rifts based on the comparatively thicker postrift sediment sequence blanketing the rift.

SUMMARY

Northeast–southwest-directed crustal extension, possibly related to a major zone of lithospheric thinning, acting during the Cretaceous, produced NW–SE-trending belts of crustal thinning and passive rift basins in central Sudan. These rifts show many similarities to the rifts of southern Sudan in terms of crustal thinning, highs in the regional gravity field, crustal extension, and age of development and should be considered as an integral part of the Central African Rift System.

The rift basins are composed of a set of individual sub-basins with half-graben geometries dominated by normal listric faulting. Maximum basin depths indicated from residual gravity models range from 1550 m for the Khartoum South Basin to 4200 m for the Kosti Basin. Separation between individual sub-basins is often marked by a complex zone of faulting forming an internal structural high referred to as an accommodation zone.

Observations made from geophysical and geological data show that the geologic features predicted by the model of McKenzie and Jarvis for passive rift develop-

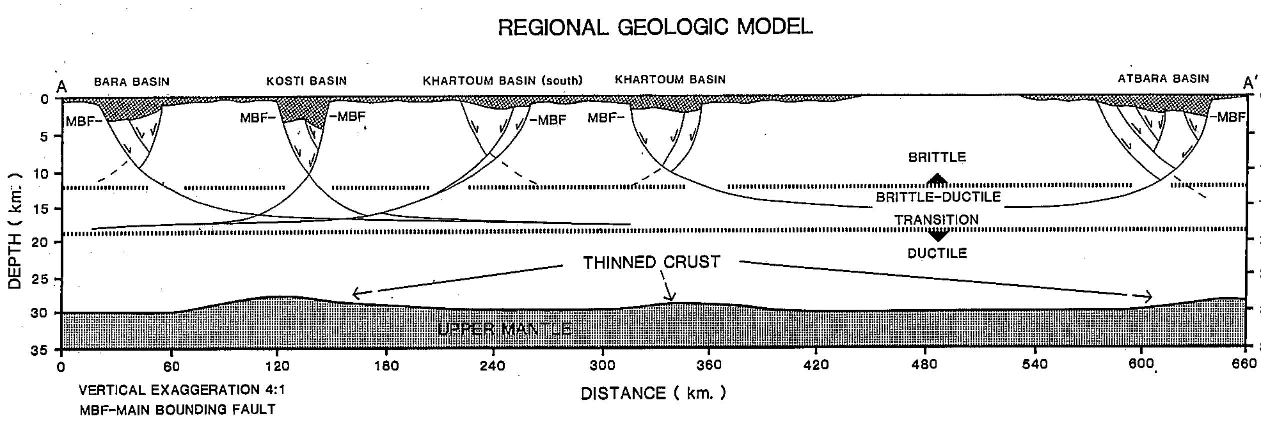

FIGURE 23.—*Regional geologic model along profile A-A', developed as a composite of the regional and residual gravity models and observed rift geometries.*

ment are present in central Sudan. These features include listric faults bounding the rift basins, thinned crust beneath rifts, and regional postrift subsidence.

Age of rifting is Cretaceous. Some geologic data indicate that the Blue Nile Rift may be older than the White Nile and Atbara Rifts. This age assignment indicates that the rifts of central Sudan formed during a major tectonic episode recorded throughout the Central African Rift System.

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REFERENCES CITED

Aboul Ela, N. M., and Mabrouk, B., 1978, Palynological studies on some Nubia Sandstone samples in Ed-Dueim area, Sudan: Revista Espanola de Micropaleontologia, v. 10, no. 3, p. 395–406.

Adighije, C. I., 1981, A gravity interpretation of the Benue Trough, Nigeria: Tectonophysics, v. 79, p. 109–28.

Ali, M. O., and Whiteley, R. J., 1981, Gravity exploration for groundwater in the Bara Basin, Sudan: Geoexploration, v. 19, p. 127–41.

Andrew, G., 1948, Geology of the Sudan: In Tothill, J. D. (ed.), Agriculture in the Sudan, Oxford University Press, London, p. 84–128.

Bally, A. W., Bernoulli, D., Davis, G. A., and Montadert, L., 1981, Listric normal faults: Oceanologica Acta, Proceedings of the 26th International Geological Congress, Geology of Continental Margins Symposium, Paris, July 7–17, 1980, p. 87–101.

Bermingham, P. M., Fairhead, J. D., and Stuart, G. W., 1983, Gravity study of the Central African Rift System: A model of continental disruption 2. The Darfur domal uplift and associated Cainozoic volcanism: Tectonophysics, v. 94, p. 205–22.

Bosworth, W., 1985a, Geometry of propagating continental rifts: Nature, v. 316, no. 6029, p. 625–27.

———, 1985b, Discussion on the structural evolution of extensional basin margins (paper by Gibbs, A. D.): Journal of the Geological Society of London, v. 142, p. 939–42.

Bott, M. H. P., 1982, The interior of the earth, its structure, constitution and evolution: Edward Arnold Limited, London, 403p.

Brown, L. D., Chapin, C. E., Sanford, A. R., Kaufman, S., and Oliver, J., 1980, Deep structure of the Rio Grande Rift from seismic reflection profiling: Journal of Geophysical Research, v. 85, no. B9, p. 4773–800.

Brown, C., and Girdler, R. W., 1980, Interpretation of African gravity and its implication for the breakup of the continents: Journal of Geophysical Research, v. 85, no. B11, p. 6443–455.

Brown, C., and Girdler, R. W., Renner, R. G. B., 1980, A gravity traverse across North Africa: Journal of Geophysical Research, v. 85, no. B11, p. 6436–442.

Browne, S. E., Bermingham, P. M., and Fairhead, J. D., 1984, Gravity measurements in Sudan by the University of Leeds: Department of Earth Sciences, University of Leeds (unpublished).

Browne, S. E., and Fairhead, J. D., 1983, Gravity study of the Central African Rift System: a model of continental disruption 1. The Ngaoundere and Abu Gabra Rifts: Tectonophysics, v. 94, p. 187–203.

Browne, S. E., Fairhead, J. D., and Mohamed, I. I., 1985, Gravity study of the White Nile Rift, Sudan, and its regional tectonic setting: Tectonophysics, v. 113, p. 123–37.

Cornacchia, M., and Dars, R., 1983, A major structural zone on the African continent. The central African lineaments from Cameroon to Aden Gulf: Geological Society of France Bulletin, v. 25, no. 1, p. 101–09.

Cratchley, C. R., Louis, R., and Ajakaiye, 1984, Geophysical and geological evidence for the Benue-Chad Basin Cretaceous rift valley system and its tectonic implications: Journal of African Earth Sciences, v. 2, no. 2, p. 141–50.

Crough, S. T., 1981, The Darfur Swell, Africa: Gravity constraints on its isostatic compensation: Geophysical Research Letters, v. 8. no. 8, p. 877–79.

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

Derksen, S. J., Lambiase, J. J., Oesleyby, T. W., Rodgers, M. R., Steed, D. A., and Wegrzyn, R. S., 1984, Rift basin review: Marathon regional exploration department report, 42p.

Dix, C. H., 1955, Seismic velocities from surface measurements: Geophysics, v. 20, no. 1, p. 68–86.

El Shafie, A. A., 1980, Contributions to the structure of central and southern Sudan: Annals of the Geologic Survey of Egypt, v. 10, p. 1133–37.

Evison, F. F., 1959, On the growth of continents by plastic flow under gravity: Geophysical Journal of the Royal Astronomical Society, v. 3, no. 2, p. 155–90.

Fairhead, J. D., 1976, The structure of the lithosphere beneath the Eastern Rift, East Africa, deduced from gravity studies: Tectonophysics, v. 30, p. 269–98.

Fairhead, J. D., 1979, A gravity link between the domally uplifted Cainozoic volcanic centres of North Africa and its similarity to the East African Rift System anomaly: Earth and Planetary Science Letters, v. 42, p. 109–13.

Fairhead, J. D., unpublished manuscript, Geophysical controls on sedimentation within the African rift systems.

Fairhead, J. D., and Stuart, G. W., 1982, The seismicity of the East African System and comparison with other continental rifts: In Palmason, G. (ed.), Continental and Oceanic Rifts, American Geophysical Union, Geological Society of America, Geodynamics series, v. 8, p. 41–61.

Flege, R. F., 1982, Regional gravity and magnetics in the Sudan, applications to petroleum exploration: Abstract PF2.4 of a paper presented at the 52nd Annual International S.E.G. meeting, Dallas, Texas.

Francis, P. W., Thorpe, R. S., and Ahmed, F., 1973, Setting and significance of Tertiary-recent volcanism in the Darfur province of western Sudan: Nature Physical Science, v. 243, p. 30–32.

Furon, R., 1963, Egypt and the Sudan: In The geology of Africa, Mafner, New York Chapter 17., p. 152–69.

Gardner, G. H. F., Gardner, L. W., and Gregory, A. R., 1974, Formation velocity and density—the diagnostic basis for stratigraphic traps: Geophysics, v. 39, no. 6, p. 770–80.

Garfunkel, Z., and Bartov, Y., 1977, The tectonics of the Suez Rift: Geological Survey of Israel Bulletin, no. 71, p. 1–44.

Geological and Mineral Resources Department, Khartoum, Sudan, 1981, Geological Map of the Sudan, 1:2 million scale, one sheet.

Gibbs, A. D., 1984, Structural evolution of extensional basin margins: Journal of the Geological Society of London, v. 141, p. 609–20.

Girdler, R. W., 1975, The great negative Bouguer anomaly over Africa: EOS Transactions, American Geophysical Union, v. 56, p. 516–19.

Gumper, F., and Pomeroy, P. W., 1970, Seismic wave velocities and earth structure on the African continent: Bulletin of the Seismological Society of America, v. 60, no. 2, p. 651–68.

Hamblin, W. K., 1965, Origin of "reverse drag" on the downthrown side of normal faults: Geological Society of American Bulletin, v. 76, p. 1145–64.

Hammer, S., 1939, Terrain corrections for gravimeter stations: Geophysics, v. 4, p. 184–94.

Harding, T. P., and Lowell, J. D., 1979, Structural styles, their plate tectonic habitats, and hydrocarbon traps in petroleum provinces: American Association of Petroleum Geologists Bulletin, v. 63, no. 7, p. 1016–58.

Hubbert, M. K., 1948, A line-integral method of computing the gravimetric effects of two-dimensional masses: Geophysics, v. 13, p. 215–25.

Isaev, E. N., and Mitwalli, M. A., 1974, Gravity studies in the Sudan, part 1, gravity bases: Democratic Republic of the Sudan, Geological and Mineral Resources Department Bulletin, no. 26, 100p.

Jarvis, G. T., 1984, An extensional model of graben subsidence—the first stage of basin evolution: In Jansa, L. F., Burollet, P. F., and Grant, A. C. (eds.), Basin Analysis: Principles and Applications: Sedimentary Geology, v. 40, p. 13–31.

Jarvis, G. T., and McKenzie, D. P., 1980, Sedimentary basin formation with finite extension rates: Earth and Planetary Science Letters, v. 48, p. 42–52.

Khattab, M. M., 1975, Sedimentary basins in northeast Kordofan, Sudan, indicated by a gravity survey: Egyptian Journal of Geology, v. 19, no. 1, p. 77–85.

Lasserie, M., 1961, Geology map of Ngaoundere-E43, SGAEF Cameroun.

Maguire, P. K. H., and Long, R. E., 1976, The structure of the western flank of the Gregory Rift (Kenya), part 1. The crust: Geophysical Journal of the Royal Astronomical Society, v. 44, p. 661–75.

Martin, A. K., Hartnady, C. J. H., and Goodlad, S. W., 1981, A revised fit of South America and south central Africa: Earth and Planetary Science and Letters, v. 54, p. 293–305.

McKenzie, D. P., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.

Mitwalli, M. A., 1969, Interpretation of the low gravity anomaly in northeast Kordofan, western Sudan: Bollettino Di Geofisica Teorica Ed Applicata, v. 11, no. 41–42, p. 119–26.

Montadert, L., Roberts, D. G., DeChaparal, O., and Guennoc, P., 1979, Rifting and subsidence of the northern continental margin of the Bay of Biscay: Deep Sea Drilling Project initial report, v. 48, p. 1025–60.

Moustafa, A. M., 1976, Block faulting in the Gulf of Suez: Fifth Egyptian General Petroleum Organization Exploration seminar, Cairo, 19p.

Nicod, M. A., 1982, Oil and gas developments in North Africa in 1981: American Association of Petroleum Geologists Bulletin, v. 66, no. 11, p. 2163–250.

Nicod, M. A., 1983, Oil and gas developments in North Africa in 1982: American Association of Petroleum Geologists Bulletin, v. 67, no. 10, p. 1795–826.

Omer, M. K., 1975, Genesis and digenesis of the Nubian Sandstone formation in Khartoum province: Democratic Republic of the Sudan, Geological and Mineral Resources Department Bulletin, no. 27, 45p.

———, 1983, The geology of the Nubian Sandstone Formation in Sudan, stratigraphy, sedimentation dynamics, digenesis: Geological and Mineral Resources Department, Khartoum, Sudan, 227p.

Parker, R. L., 1973, The rapid calculation of potential anomalies: Geophysical Journal of the Royal Astronomical Society, v. 31, p. 447–55.

Qureshi, I. R., and Sadig, A. A., 1967, Earthquakes and associated faulting in central Sudan: Nature, v. 215, p. 263–65.

Reynolds, D. J., and Rosendahl, B. R., 1984, Tectonic expressions of continental rifting: (abstract) EOS Transactions, American Geophysical Union, v. 65, no. 45, p. 1116.

Rosendahl, B. R., Reynolds, D. J., Lorber, P. M., Burgess, C. F., McGill, J., Scott, D., Lambiase, J. J., and Derksen, S. J., in press, Structural expressions of rifting: lessons from lake Tanganyika, Africa: In Reid, I., and Frostick, L. F. (eds.), Geologic Society of London, special paper.

Shadul, S. A., 1978, Integrated geology of central Sudan: Remote Sensing Institute, South Dakota State University report, December 1978, 48p.

Slettene, R. L., Wilcox, L. E., Blouse, R. S., and Saunders, J. R., 1973,Agency, Washington, D.C.

Strojexport, 1977, Geophysical investigations of groundwater structures—central and northern parts of the Upper Nile province, fifth stage, Prague.

Talwani, M., Worzel, J. L., and Landisman, M., 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone: Journal of Geophysical Research, v. 64, no. 1, p. 49–59.

Vail, J. R., 1978, Outline of the geology and mineral deposits of the Democratic Republic of the Sudan and adjacent areas: Overseas Geology and Mineral Resources, Institute of Geological Sciences, no. 49, 68p.

van Overmeeren, R. A., 1981, A combination of electrical resistivity, seismic refraction, and gravity measurements for groundwater exploration in Sudan: Geophysics, v. 46, no. 9, p. 1304–13.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range Province; nappe tectonics in an extending orogen: Nature, v. 291, p. 645–48.

Wernicke, B., and Burchfiel, B. C., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, no. 2, p. 105–15.

Whiteman, A. J., 1971a, The geology of the Sudan Republic: Clarendon Press, Oxford, 290p.

Whiteman, A. J., 1971b, Structural geology of Sudan: In Tectonics of Africa, UNESCO, Earth Sciences, no. 6, p. 433–45.

Woollard, G. P., 1966, Regional isostatic relations in the United States: In Steinhart, J. S., and Smith, T. J. (eds.), The earth beneath the continents, Geophysical Monograph, no. 10, American Geophysical Union, Washington, D.C., p. 557–94.

———, 1979, The new gravity system—changes in international gravity base values and anomaly values: Geophysics, v. 44, no. 8, p. 1352–66.