

ARCHITECTURE OF AFRICAN RIFTS WITH SPECIAL
REFERENCE TO THE BRAZILIAN MARGIN*

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The East African Rift is composed of zones of linked half-graben. The key to interpreting seismic data from such areas is recognizing that linking geometries have a direct bearing on rift basin morphology. Dip profiles across overlapping, opposing half-graben show two half-graben that face each other. This creates an apparent full-graben with some sort of complex axial structure, usually antiformal in character. Such structures have been termed "interference accommodation zones" (INAZ) because they accommodate the subsidence of the facing half-graben. In some cases, the accommodation can involve transverse, strike-slip, and compressional tectonics, although the overall stress regime is extensional. Depending upon the geometry, INAZ's can be very large features and they often terminate in platforms, which serve as the access routes for fluvial clastics entering rift basins with this type of geometry. Dip profiles across non-overlapping, opposing half-graben, show two half-graben facing away from each other. They are usually separated by backbones of relatively unsubsided country rock, termed "isolation accommodation zones" (ISAZ). These can be sites of considerable strike-slip faulting. Unlike INAZ's, which usually are not modern-day barriers to fluvial sediment dispersal, ISAZ's often act as nearly complete dams throughout the history of a rift. Fluvial clastic input to half-graben linked in this fashion is mainly from the shoaling or ramping sides. Although it is common for one sense of polarity to dominate in African rift zones, there is never an exclusive direction of asymmetry and usually no more than two adjacent half-graben display the same polarities. This contrasts with the Triassic rift basins of the Eastern U.S., where all but a few half-graben have their border fault systems on the west. The difference probably relates to reoccupation of Paleozoic thrust planes in the Triassic case, and lack of one systematic low-angle thrusts in the old, cold, and brittle crust of pre-rifted East Africa. The areas between

similar polarity half-graben are often platforms and fluvial clastics may enter these half-graben across such platforms, as well as from their shoaling sides.

These concepts are very useful in analyzing rifts such as the Recôncavo Basin. The style of linking determines the loci of fluvial clastic input, which bears on the distribution of reservoir rocks. Also, the nature of interference accommodation zones is dynamic – these features evolve with the adjacent depocenters, usually remaining high relative to the depocenters. The stratigraphic and hydraulic consequences of this, combined with the scale of these features and the fact that they merge into platforms, make them primary targets for petroleum exploration in rifts. The Agua Grande field in the Recôncavo Basin is an excellent example. On the other side of the coin are the isolation accommodation zones, which usually are poor synrift exploration targets. Another value of these rifting concepts is that they offer new insight into the progression from continental rift to juvenile ocean basin to passive continental margin. For example, facing half-graben arrangements, hence INAZ's, are a necessary step toward successful rifting, which probably begins with juvenile half-graben expressions and ends with the success of one spreading center and abandonment of one or more others. A related application is the realization that symmetric conjugate rift margins are an unlikely outcome of ripping the Tanganyika or Malawi rifts apart. Instead, asymmetry should rule. Most of the rifted terrain probably is left on only one of the margins, in a pattern that alternates between the margins along strike. The Cabinda/Campos case is an excellent example.

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PHYSICAL MODELLING OF EARLY CRETACEOUS CONTINENTAL BREAKUP
BETWEEN SOUTH AMERICA AND AFRICA*

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On the basis of seismic reflection profiles and field observation of fault kinematics, Szatmari *et al.* (1985, 1987) modified the early Cretaceous pole position proposed by Rabinowitz & LaBrecque to lie near São Luís, Maranhão, on the Equatorial Margin of northeastern Brazil. The new pole position, for pre-Aptian time, is in the interior of northeastern Brazil, near Lavras da Mangabeira, Ceará, at 38.9°W and 6.9°S.

The effect of an Euler pole situated within the separating continents has been little studied either theoretically or experimentally. Such effects include reactivation of ductile wrench zones in the Precambrian basement, especially near the pole, by horizontal movement of crustal and lithospheric blocks. This movement opens up isolated rifts and creates local compressive structures between the laterally dislocated and slightly rotated blocks.

The present study tests these effects by physical modeling following techniques developed by Cobbold and coworkers. Two layers are used: a ductile lower layer made of a special silicone and representing the lower crust and portions of the mantle lithosphere; and an upper layer made of sand and representing the upper crust. In the experiments, a thin acrylic sheet cut to the shape of eastern South America is rotated in a round dish about the proposed pole. Both the rotating sheet

and the bottom of the dish outside are uniformly covered, before the start of the experiment, by silicone and sand. During the experiments, rotation rates of 10^{-3} to 10^{-4} degree per hour are maintained from several hours to several days.

The experiments effectively recreate many of the structural features of South America's Eastern and Equatorial Margins. A structural high forming west of the pole along the Equatorial Margin correlates with the Ferrer-Urbano Santos Arch, while a platelet breaking away from the South American continent corresponds to the Northeast Brazilian Microplate. Along the Eastern Margin, between Salvador and Recife, a complex systems of wrench faults and tensional fractures form, which correlate extremely well with the fault pattern of the Sergipe-Alagoas basin. Several of the strike slip faults penetrate deep inland, recreating known inland faults and grabens.

This study shows the value of physical modeling in the analysis of complex tectonic problems.

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THE SOUTH ATLANTIC RIFTING*

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The history of the South Atlantic ocean has its origin in the Jurassic, nearly 200 Ma. when the African and South American continents began their separating process. From this process, known as the rifting phase, developed nearly always in a tensional tectonic environment, a framework was defined that has influenced the entire geology of this ocean.

A model of evolution for the rifting phase is proposed in this paper, which includes the accumulation stages of energy accompanied by crustal stretching (ductile behavior), followed by stages of energy release through faults (brittle behavior). The possible sedimentary environments involved in each of these stages will also be discussed.

The importance of the large crustal discontinuities in the development of the rifting, acting or not as energy release zones, is another topic to be mentioned. Emphasis will be placed on the Curitiba-Maringá fault zone, its influence on

the formation of the São Paulo Plateau and the origin of basic magmatism of the Paraná Basin.

A tentative comparison will be between some observed facts along the evolution of the Atlantic ocean and its possible causes in the rifting phase. Consequently, proposals will arise for an explanation of the limits of the evaporitic basin on the west coast, depositional limits of the basins; uplifting of the Serras do Mar and Mantiqueira in the Tertiary, etc...

Finally, several evidences related to the age of the first manifestations of the rifting of the South Atlantic will be discussed.

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THE NORTHEASTERN BRAZIL AND GABON BASINS: A DOUBLE RIFTING SYSTEM ASSOCIATED WITH MULTIPLE CRUSTAL DETACHMENT SURFACES

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Analysis of structural stratigraphic and gravimetric data from the Recôncavo, Tucano, and Sergipe-Alagoas basins in northeastern Brazil and the Gabon basin in Africa shows that these basins originated in a double rifting system associated with multiple crustal detachment surfaces, and that the direction of dip of the detachment surfaces was reversed at the Vaza-Barris transfer fault. This geometry is in agreement with models and data from modern rifts, but it requires the existence of a predominantly extensional stress regime in the northern part of the South Atlantic during the early stages of oceanic evolution. Evidence for the existence of such a stress regime is given by application of kinematic constraints to

Early Cretaceous reconstructions of the South Atlantic Ocean.

Interpretation of the regional geologic setting suggests that the double rifting system and the point of final continental rupture are controlled by the pre-existing structural orientation of the tectonic provinces in the Precambrian basement.

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BENUE TROUGH OBLIQUE RIFTING, NE BRAZIL INTERIOR BASINS AND THE GEODYNAMIC EVOLUTION OF THE EQUATORIAL DOMAIN OF THE SOUTH ATLANTIC*

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The Benue Trough has been the object of several geodynamic models, documented either as a graben, a rift or an aulacogen basin, a wrench fault basin, or an active margin; except the last one, each of these definitions could be accepted as none had been precisely argued. Updated field and laboratory data acquisition now allow to enlight the geodynamic setting of the Benue Trough in an oblique rifting system. It represents a fundamental inland marker, part of the M.A.R.S. (Mid African Rift System), in the evolution of the Northern South Atlantic in its Equatorial Transform Domain.

Since the Jurassic first – with the emplacement of the Younger Granites of the Jos Plateau –, and namely from the Early Cretaceous times onwards, the Nigerian Pan-African Mobile Belt has been subject to a generalized extensional tectonic regime. However, two compressive events occurring during the Santonian mainly and the Maastrichtian later on have generated discontinuous fold sets following the Trough's elongation; they initiate the shifting of the main depocenter zones.

It is shown that the major active faults inside the Benue Trough are Pan-African fracture zones reactivated within successive stages. These faults are commanding the location and the evolution of polyphased sedimentary basins related to a differential crustal thinning.

A comparison is made between the Benue Trough and the intracontinental basins from Northeastern Brazil in their respective tectonic frameworks and sedimentary evolutions. Each of the two contiguous domains contribute to define the kinematic characteristics of the Northern South Atlantic transform zone joining the Central Ocean at the end of the Early Cretaceous times.

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NEW DATA ON SEDIMENTATION, PALEOENVIRONMENT AND STRATIGRAPHY OF THE CHAPADA DO ARARIPE*

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Several publications are dealing with the origin of the sedimentary formations from the chapada do Araripe.

All authors admit a fluvial origin for the Missão Velha Formation and a lacustrine origin for the Crato Member of the Santana Formation.

Opinions are different in respect to the following cases. For some authors, the gypsum (Ipubi Mb.), as well as the marls, clays, and carbonates, generally dolomitic, of the Romualdo Member are of marine origin. For other authors a continental origin is more suitable.

Our data confirm the fluvial environment of the Missão Formation and a lacustrine one for the Crato Member. The palynological assemblages allow us to propose an Aptian age for the black shales of the middle part of the Missão Velha Formation.

Above the gypsum there are 15 m of sediments very rich in freshwater ostracods (including *Theriosynoecum*); these

would favor a lacustrine environment for the gypsum and the overlying fish beds. Isotopic analyses are being carried out in order to confirm these data.

The upper part of the Romualdo Member (Albian) shows, in contrast, some marine influences.

The chapada do Araripe is an endorheic basin overlying a transcurrent-faulted basement and includes two megasequences separated by an unconformity marked by erosions and microconglomerate development. The lower sequence is fluvial at the base, then lacustrine and finally restricted at the top. The upper sequence is sharply truncated by the Exu Formation (siliciclastic, fluvial in origin).

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WORKSHOP TO DEVELOP SCIENTIFIC DRILLING INITIATIVES IN THE SOUTH ATLANTIC AND ADJACENT SOUTHERN OCEAN: A REPORT*

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During April 6-8, 1987, a group of approximately 50 scientists from nine countries met at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, to discuss the future of scientific ocean drilling in the South Atlantic and adjacent Southern Ocean. This workshop was endorsed by the Atlantic Regional Panel of Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES), an organization of the marine scientific communities of 18 nations which is responsible for controlling the activities of the Ocean Drilling Program (ODP). ODP is the successor to the Deep Sea Drilling Project (DSDP), which drilled 624 sites in the world's oceans during 1968-1982. A new, larger, and more comprehensive drilling platform is being used by ODP, the *D/V JOIDES Resolution*. With the *Resolution*, ODP can drill almost anywhere in the oceanic realm. In fact, several successful drilling cruises have been completed in the Antarctic. Funding for U.S. participants to the workshop came from JOI-USSAC (the United States Scientific Advisory Committee of Joint Oceanographic Institutions, Inc., the American counterpart to JOIDES), while other participants were supported by funding agencies in their respective nations.

After a plenary session during the first day which included a number of invited summary lectures by recognized authorities on the evolution of the South Atlantic, workshop participants were divided by the convener into four topical groups: evolution of oceanic lithosphere/tectonics; physical stratigraphy/development of the sediment record; biostratigraphy; and geochemistry. These groups spent the next two days identifying the major scientific themes involved with the geologic evolution of the South Atlantic and developing drilling strategies required to address them. Petrobrás personnel contributed substantively to discussions in both the physical stratigraphy and tectonics groups. On the afternoon of the third day, representatives of each group delivered their findings during a second plenary session. These findings have been summarized. Following these reports, a general discussion identified the similarities in the diverse group presentations, and the decision was made to keep their input separate and distinct for the purposes of the written workshop report. That report, a summary of the workshop's activities, was completed and disseminated to workshop participants and the rest of the scientific drilling community during the fall of 1987.

The South Atlantic workshop is one of a series of workshops planned by JOIDES which are designed to organize scientific input to ODP. These workshops are essential for the efficient planning of geophysical surveys which must precede the drillship's return to the Atlantic and adjacent oceans in the early 1990's.

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THE CRETACEOUS OFF-SHORE PARÁ-MARANHÃO, BRAZIL:
BIOSTRATIGRAPHY AND PALEOECOLOGY*

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The sediments drilled off-shore Pará and Maranhão (equatorial continental margin, Brazil) may be ascribed to four major sequences as defined for the Brazilian continental margin by Ponte & Asmus (1978): the basal non-marine/evaporitic sequence of the rift stage (Alagoas in age, *Sergipea variverrucata* and *Vitreisporites signatus* zones), whose upper part is already of paralic character; the carbonate shelf sequence (Early-Middle Albian, *Steevesipollenites alatiformis*/*Hedbergella* aff. *H. gorbachikae* zones) comprising paralic to shallow neritic sediments; an evidence of the first marine incursion coming from the east, the Turonian-Santonian transgressive sequence, with neritic sediments at the base and neritic/upper bathyal sediments at its upper part (*Tricolpites* *S.427*/*Globotruncana inornata* and *G. concavata*/*Victorisporites roberti* zones); and the Campanian to Recent prograding sequence, with middle/outer neritic sediments being deposited during terminal Cretaceous time on the western part of the basin and upper/middle bathyal ones its eastern part (the Cretaceous section belonging to the Early Campanian *Auriculidites reticulatus* Zone and to the Maastrichtian *Tricornites elongatus*/*Globotruncana fornicata* and *G. gapsseri*/*Rugoglobigerina reicheli*/*Proteacidites longispinosus* zones).

The sequences' boundaries are characterized by regional seismic discontinuities, whose biostratigraphic dating reveals the existence of several hiatuses: neither Late Albian-Cenomanian nor Latest Santonian-basal Campanian sediments have been found; the gap in time between the non-marine/evaporitic and the carbonate shelf sequences could not be estimated. Some other important regional hiatuses correspond to the Coniacian, Late Campanian, and Latest Maastrichtian times. This last one and that between the transgressive and the prograding sequences are of erosive character.

Although the first marine sediments had been deposited in the studied area during Early/Middle Albian time, it was only from the Turonian on that doubtless transgressive sedimentation took place in a widespread neritic environment. The transgression has reached its maximum at Middle Santonian time (86 Ma) as suggested by the landward shifting of paleobathymetric contour lines; a very fast progress of the coastal onlap, with bathyal sediments transgressing over shallow neritic ones has been identified on several wells at this time. Despite of this, the paleobathymetry continues to increase up to Early Tertiary time (Abreu *et al.* 1986), as the subsidence still being greater than sediment infilling (final stage of thermal subsidence?). The Cretaceous profile of the ocean's floor is remarkably different from that of Middle Eocene to Recent times: from the Santonian to the Maastrichtian a narrow shallow neritic platform (19 to 30 m deep) is bordered by a much steeper slope of middle/outer neritic environment (30 to 200 m), on whose base the ocean's floor lies in upper bathyal paleobathymetry (from 200 to 500 m).

Restriction to the development of benthic life has been recorded during the Early/Middle Albian and during the Turonian.

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CRETACEOUS EVOLUTION OF THE BRAZILIAN ATLANTIC MARGIN AS DEDUCED FROM THE CARBONATE RECORD*

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The study of carbonate rocks is considered an useful tool for the understanding of South Atlantic evolution during Cretaceous times.

The oldest Cretaceous carbonate rocks of the Brazilian Atlantic margin were deposited during the rift phase in the Recôncavo Basin. Here, shallow lacustrine carbonates of the Rio da Serra Stage are found in the Candeias Formation. They consist of oncolitic and oolitic calcirudites and calcarenites. Ostracod limestones of Aratu age occur throughout the basin, where regarded as good marker-beds. Also the black shale sequence of the Buracica Stage is a good lithologic marker, and includes some beds with an abundant non-marine foraminifera monofauna associated with ostracods characteristic of Petrobrás biozone 007.2.

During the transition (marine/non-marine) phase, coquina-limestone does occur in Campos, Sergipe, and Potiguar basins. Although pelecypod shells are the prevailing constituents, gastropod, and ostracod remains are also present. During the evaporitic phase, several ostracod and algal laminite beds were deposited; beside molluscs, fragments of echinoderms, and foraminifera have been also found in the Sergipe-Alagoas Basin.

The Cretaceous marine phase is represented by several carbonate units. Starting from the Campos Basin, an Early Albian shallow water oncolitic limestone testifies to the beginning of Cretaceous marine sedimentation in a restricted platform. This unit is covered by a deeper water calcilutite

facies as a response to the Middle-to-Upper Albian transgressive event. The calcilutite consists of planktonic foraminifera and calcispherulid remains, and occurs throughout the Brazilian continental margin. Although in the Campos Basin this deep water unit records the close of Cretaceous carbonate deposition, it only represents the older section of the Albian/Cenomanian marine carbonates in the Sergipe, Potiguar, and Barreirinhas basins. Here, they are covered by shallow water carbonates which include some small, patchy reefs built by corals, corallinacean, and solenoporacean red algae. The new sequence displays a far greater biotic diversity than the carbonates of the Campos Basin.

During the Late Cretaceous, carbonate units were deposited in Sergipe and Potiguar basins. Outcrops of outer shelf deposits are found in the former, shallow water equivalents being absent there due to erosion. In the Potiguar Basin, Late Cretaceous units consist of shallow lagoonal and tidal flat deposits.

Maastrichtian carbonates along the coast between Recife and João Pessoa represent the latest Cretaceous carbonate deposits of the Brazilian continental margin.

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