Mascle, J., Lohmann, G.P., Clift, P.D., et al., 1996
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1. INTRODUCTION[1]

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Drilling the Côte d'Ivoire-Ghana transform continental margin in the eastern equatorial Atlantic Ocean had both tectonic and paleoceanographic objectives. The main tectonic objective was to better understand the evolution of transform continental margins. Transform faults represent the third major category of plate boundaries, but are less well understood than either divergent or convergent examples. Among transform boundaries, transform continental margins in particular are poorly known and had never previously been investigated by scientific drilling. Drilling in such a setting served to constrain the structure and evolution of the ocean-continent transform boundary, and in particular its deformational history, vertical movements, and subsequent post-rift sedimentary record. The main paleoceanographic objective was to document changes in deep and intermediate waters passing through the eastern equatorial Atlantic. The history of intermediate waters is not well documented outside the North Atlantic Ocean, and the changing geometry of the eastern Atlantic basins since continental breakup in Early Cretaceous times is likely to have affected their ventilation by deep waters.

The concept of a transform (or sheared/translational) continental margin as a specific type of continent/ocean boundary has progressively developed since the 1970s. Geophysical surveys from several transform margins clearly demonstrate that these continental borderlands are radically different from normal passive margins, in terms of their crustal structure, deformation, subsidence, and sedimentation history.

Within the past 20 years, several marine geophysical cruises conducting gravimetry, seismic refraction, and reflection profiling, as well as deep submersible dives, have been devoted to the study of the equatorial African transform margins (Fail et al., 1970; Arens et al., 1971; Machens, 1973; Delteil et al., 1974; Emery et al., 1975; Mascle, 1976; Klingebiel, 1976; Blarez, 1986; Blarez et al., 1987; Mascle and Blarez, 1987; Mascle et al., 1988; Mascle et al., 1989; Basile, 1990; Basile et al., 1992; Mascle et al., 1993, 1994; Basile et al., 1993; Mascle et al., 1995) and of their conjugate along the northern Brazilian Margin (Ponte and Asmus, 1978; Zalan et al., 1985; Costa et al., 1990). From these studies two main morpho-structural features typical of transform margins can be recognized along the Côte d'Ivoire-Ghana Margin (Figs. 1, 2), namely (1) a lateral structural continuity between a major oceanic fracture zone and a prominent, linear, and steep continental slope, which results in a very steep and narrow (20–30 km) transition between a continental domain and an adjacent oceanic abyssal plain, indicating a very sharp crustal transition between thick or partially thinned continental crust and oceanic lithosphere, and (2) a morphologically well expressed marginal ridge, bounding the transform margin, along an adjacent extensional basin (Deep Ivorian Basin). The steep marginal ridge results from translational stresses that were active between two continents along active transform faults. During rifting and ocean opening, such evolution can be schematized into three main stages (Fig. 3; Mascle and Blarez, 1987):

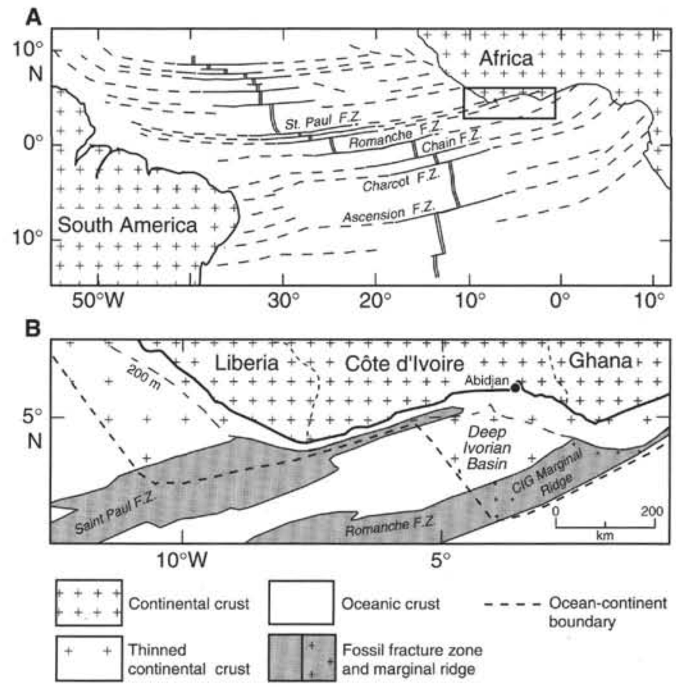

Figure 1. Geodynamic, geological, and bathymetric framework of the Côte d'Ivoire-Ghana Transform Margin. Boxed region in (**A**) is shown in more detail in (**B**).

Stage 1: An intra-continental active transform fault (Stage A on Fig. 3). This results in a contact between two thick continental plates. In this case, the transform boundary of the extensional basin is submitted to shear stresses and accompanies tectonic uplift to create a bordering marginal ridge.

Stage 2: A continent-ocean active transform fault contact (Stage B on Fig. 3). In this setting, the proximity of hot oceanic lithosphere may have induced important vertical readjustment of the nearby continental margin.

Stage 3: An inactive continent-ocean transform fault (Stage C on Fig. 3). At this stage the margin segment becomes a passive transform margin, experiencing relatively gradual thermal subsidence.

Such evolution implies successive crustal/lithospheric contacts that should have produced strong thermal and pressure contrasts,

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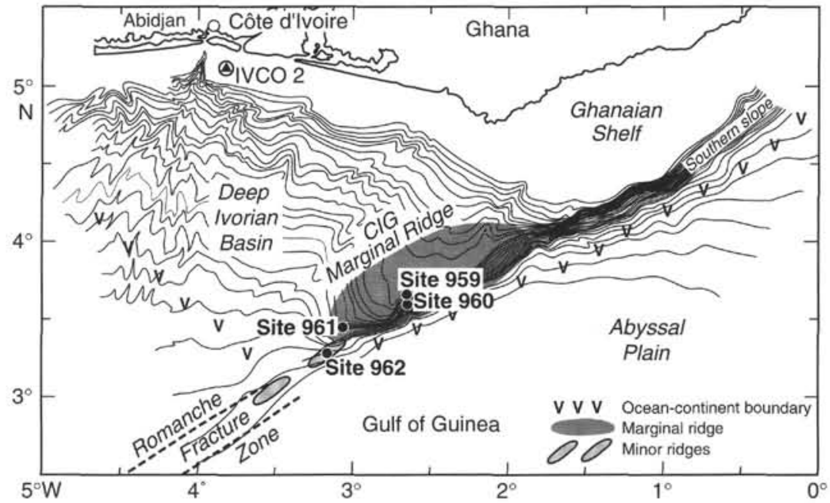

Figure 2. Simplified bathymetry and main morpho-structural domains of the Côte d'Ivoire-Ghana Transform Margin. The solid circles show locations of Leg 159 sites, the triangle the location of Hole IVCO2. The V's indicate the continent-ocean transition, which is older west of the Deep Ivorian Basin than southward in the Gulf of Guinea.

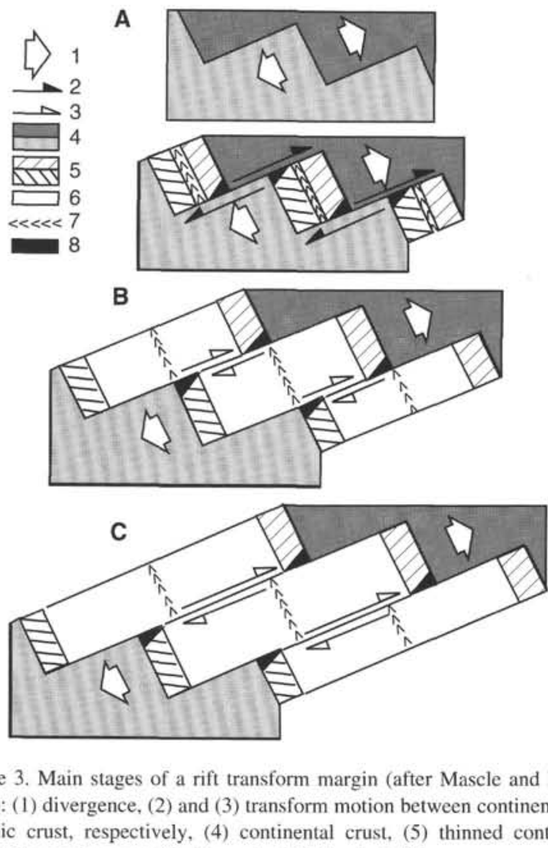

Figure 3. Main stages of a rift transform margin (after Mascle and Blarez, 1987): (1) divergence, (2) and (3) transform motion between continental and oceanic crust, respectively, (4) continental crust, (5) thinned continental crust, (6) oceanic crust, (7) ridge axis, (8) Marginal Ridge.

which in turn should be recorded in the sedimentary record during the margin's creation and subsequent evolution (Sage, 1994).

GEOPHYSICAL AND GEOLOGICAL BACKGROUND

The Côte d'Ivoire-Ghana Margin results from major transform motion between plate boundaries. This motion is still active today along the Romanche Fracture Zone, which offsets the Mid-Atlantic Ridge by 945 km (Fig. 1A; Fail et al., 1970). The area of recent investigation along this margin is the Côte d'Ivoire-Ghana Marginal Ridge (CIGMR), which corresponds to a transition between a laterally thinned continental crust and adjacent oceanic crust (Fig. 1B). The setting of the present-day Marginal Ridge includes a fossil ridge that connects laterally with the extinct Romanche Fracture Zone.

The seismic stratigraphy and existing tectonic models of the area drilled during Leg 159 are chiefly based on investigations by a series of earlier geophysical cruises (Fig. 4). The site survey data for Leg 159 were collected in 1983 by the *Equamarge I* cruise (Blarez, 1986; Blarez et al., 1987; Mascle and Blarez, 1987; Mascle et al., 1988), in 1988 by the *Equamarge II* cruise (Mascle et al., 1989; Basile et al., 1989; Popoff et al., 1989; Pontoise et al., 1990; Basile, 1990; Basile et al., 1992, 1993), in 1990 by the *Equasis* and *Equaref* cruises (Mascle et al., 1995), in 1991 by *C. Darwin* cruise 55, and in 1992 by the *Equanaute* cruise (Mascle et al., 1993, 1994). A few results from the Brazilian conjugate margin, explored by PETROBRAS (Ponte and Asmus, 1978; Zalan et al., 1985; Costa et al., 1990), also were important in framing the scientific objectives of the cruise.

Tectonics

The Côte d'Ivoire-Ghana continental margin is made up of two distinct northern and southern segments. The northern domain includes most of the eastern Ivorian continental slope and southwestern Ghanaian upper slope, and is known as the Deep Ivorian Basin. The southern segment bounds the previous one toward the south and follows a northeast/southwest direction. This segment is known as the Côte d'Ivoire-Ghana Marginal Ridge.

The Deep Ivorian Basin is an extensional margin, thinned in the upper crust by dip-slip faults trending north-south to northeast-southwest. These faults bound tilted blocks and half-grabens, which are infilled by thick syn-tectonic sediments (Unit A; Figs. 5, 6). To the south, the fossil Marginal Ridge is a 130-km-long and 25-km-wide prominent feature that towers over the Deep Ivorian Basin by 1300 m and over the adjacent oceanic crust by more than 4000 m (Figs. 2, 7, 9).

The regional structures of the transform margin are linked to the westward thinning of the adjacent divergent basin. East of 2°10′W, the transform border is expressed by a narrow shelf. Between 2°10′W and 2°45′W, the transform zone is chiefly expressed by the Marginal Ridge. West of 2°45′W, the ridge top is progressively westward-dipping like the bordering Deep Ivorian Basin (Fig. 2). Due to the chaotic facies of the deep acoustic units, little is known about the internal structure of the Marginal Ridge from single-channel seismic lines. Migrated multichannel seismic lines have greatly improved our knowledge of its pseudo-basement.

East of 2°10′W (Line MCS MT03; Fig. 8), transform motion has generated flower structures at the Deep Ivorian Basin-CIGMR transition. To the north, these strike-slip faults become transpressional

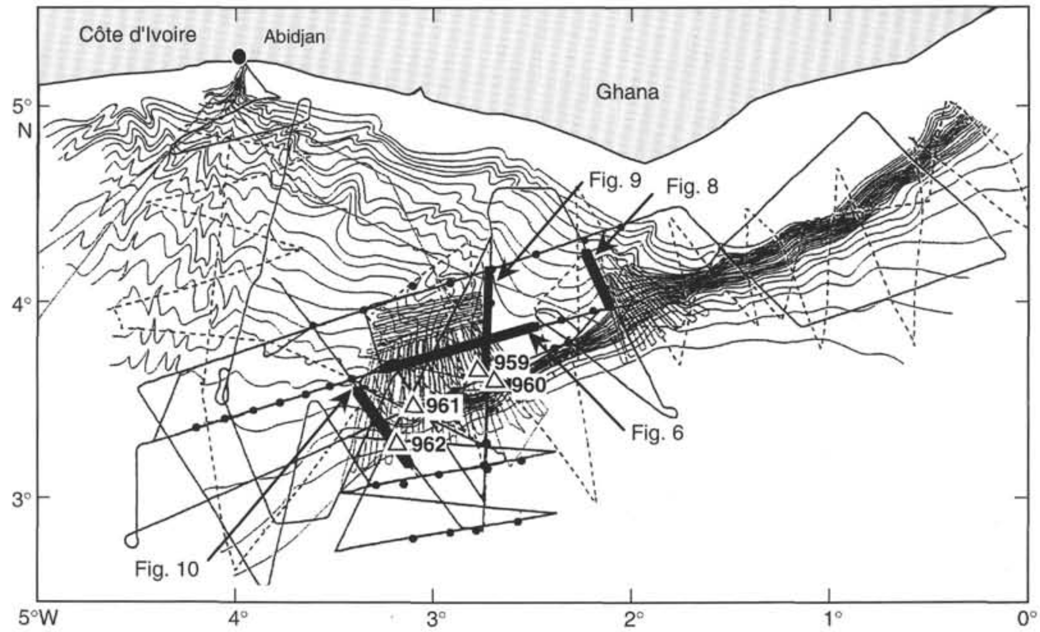

Figure 4. Recent geophysical data collected on the Côte d'Ivoire-Ghana Transform Margin shown on a simplified bathymetric map of the margin. Triangles = the first priority sites of Leg 159; dots = single-channel seismic lines (*Equamarge,* 1983); dashed line = single-channel seismic lines and swath bathymetry (*Equamarge,* 1988); solid lines = multichannel seismic reflection lines (*Equasis,* 1990); filled circles = location of ocean bottom seismometer (OBS) deployments (*Equaref,* 1990). The *Equanaute* dives were performed along the southern slope of the Côte d'Ivoire-Ghana Marginal Ridge in the two areas surveyed in swath bathymetry.

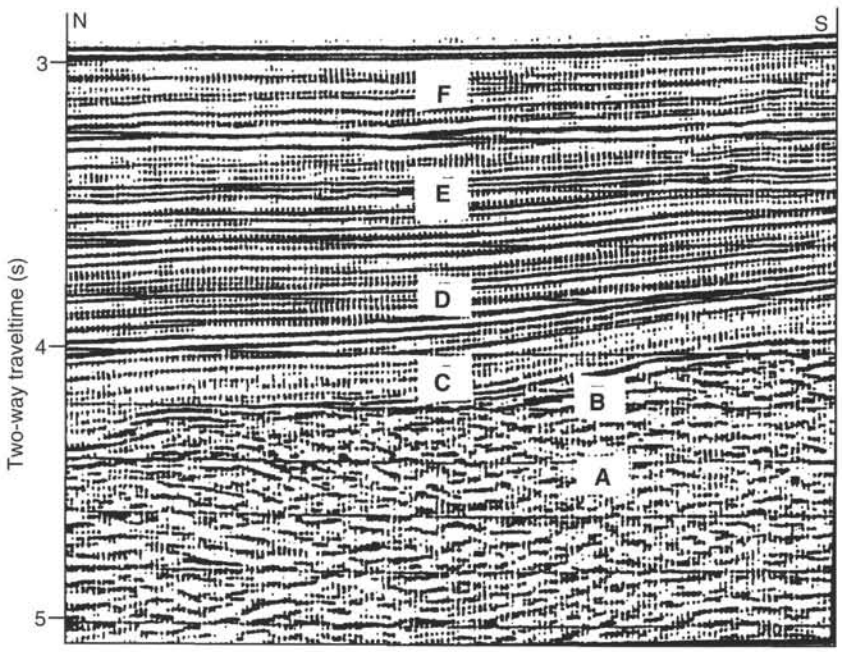

Figure 5. The main sedimentary units (A–F) and probable correlations in the Deep Ivorian Basin and Côte d'Ivoire-Ghana Marginal Ridge (after Basile et al., 1993).

and exhibit reverse slip. The associated folds are arranged en échelon and indicate right-lateral movement. To the south a wide (>10 km) and deep (1 km) feature appears that may represent an infilled intracontinental transform valley. The southern limit of this valley probably lies near the top of the actual southern continental slope, where the deformation (e.g., folding, vertical fracturing, fracture cleavage) observed during the scientific dives is more intense than southward, out of the transform valley.

Most of the strike-slip fault activity occurred during the sedimentation of the basal units, A and B. The reverse strike-slip faults were active during deposition of the deepest sequences, which were uplifted during sedimentation and cut by later faults. An additional uplift of the basal sequences produced an unconformity that has been overlain by undeformed units (Fig. 5).

Between 2°10′W and 2°45′W (MCS Line MT02; Figs. 5, 9), along a north-south cross section of the Marginal Ridge, three tectonic domains can be distinguished, including a western prolongation of the transform valley observed toward the east. At this point the equivalent of the transform valley is located at the boundary between the Deep Ivorian Basin and the Marginal Ridge. The valley cuts into the deepest unit and is partly infilled by both faulted and unfaulted upper sediments. The northern slope of the Marginal Ridge is made by

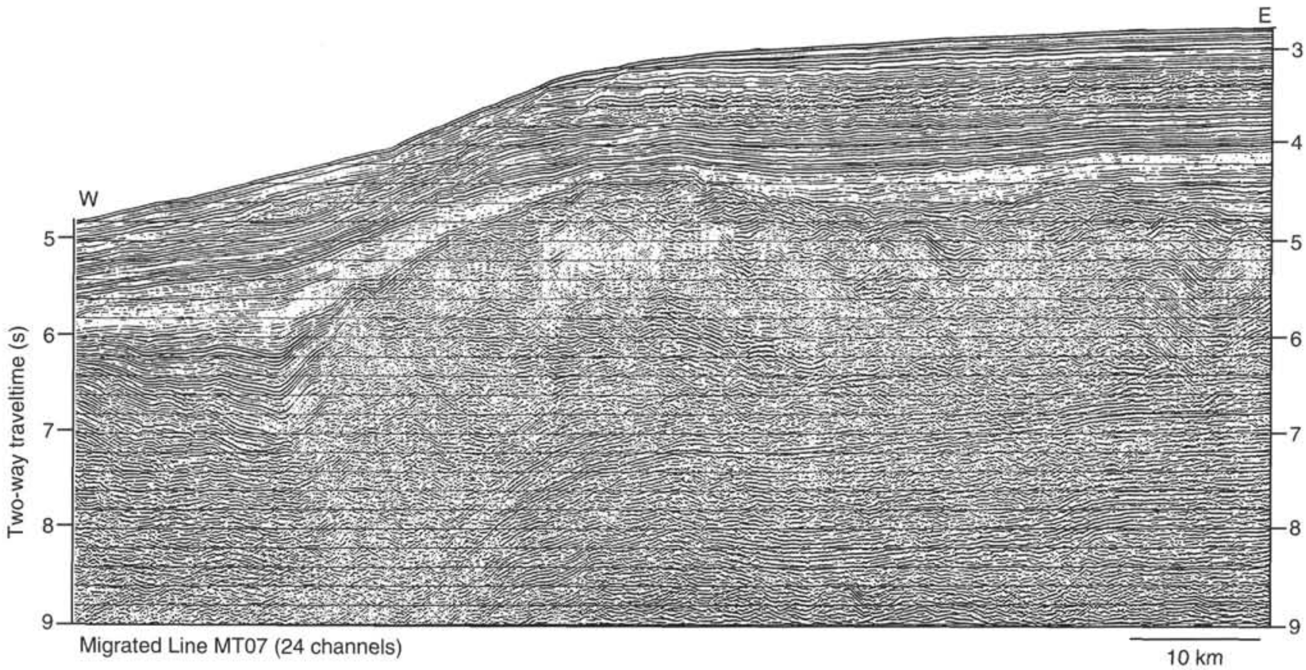

Figure 6. Section of migrated (24 channels) MCS Line MT07 (*Equasis,* 1990) across the upper continental slope of the Côte d'Ivoire deep extensional basin (see location on Fig. 4); the section shows a large rotated block and accompanying half-graben; this last is infilled by syn-rift Unit A, overlain unconformably by Unit B and subsequent post-rift sediments.

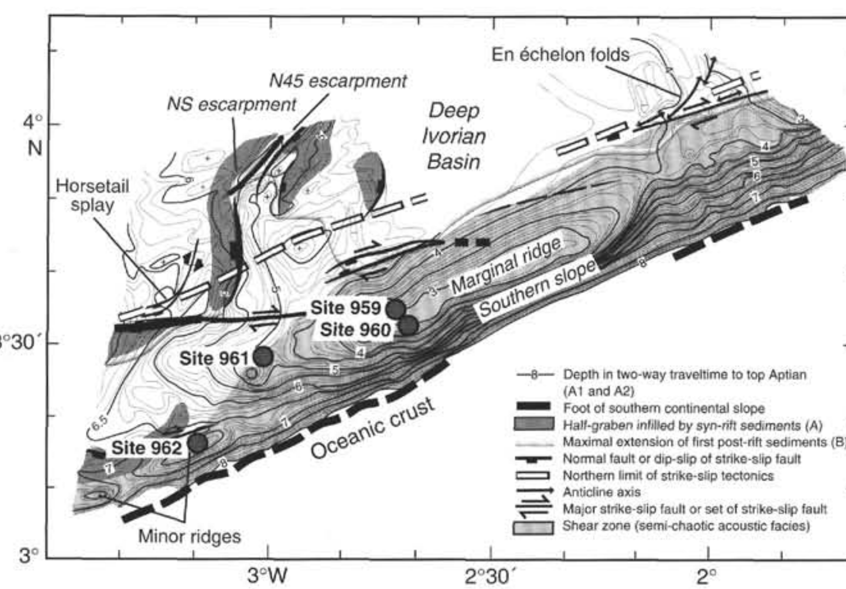

Figure 7. Simplified structural sketch of the Côte d'Ivoire-Ghana Marginal Ridge and surroundings (after Basile et al., 1993). Depth is shown in two-way traveltime to the top of syn-rift Unit A. Leg 159 sites are shown.

thickening of the lower unit toward the south. This thickening has resulted in the growth of a swell with, at its top, sedimentary lenses prograding to the north and associated distal fans developed along its northern slope.

North of the Marginal Ridge the presence of the Deep Ivorian Basin and the apparent northward progradation of sediments suggest that the detrital material originated from the Brazilian Shelf, which was located just to the south at the time of intracontinental transform faulting. Deep dive observations and seismic data tend to substantiate the idea that deformation (fracturing and folding) increases upslope toward the ridge top, where strike-slip activity was probably also concentrated.

Multichannel seismic lines (Figs. 6, 9) also show that the first undeformed unit is restricted to the Deep Ivorian Basin and northern slope of the Marginal Ridge. Thus, sedimentation proceeded simultaneously by aggradation in the Deep Ivorian Basin, with sediments originating from African coasts, and by progradation, with sediments probably derived from erosion of the ridge top. Units C through F are restricted to the Deep Ivorian Basin and northern ridge slope.

West of 2°45′W, to the west of the Marginal Ridge, the southern border of the transform margin includes several en échelon, spaced, minor, buried, acoustic ridges (Figs. 7, 10). These tower over the oceanic crust to the south and over a thick (about 2 km) basinal section to the north. These ridges are thought to originate in connection with transform motion, but different hypotheses can be made about their nature and deformational history. Are these ridges continental or oceanic, basement or intensively deformed sediments? Did these ridges initiate during the rifting of the Deep Ivorian Basin, during continen-

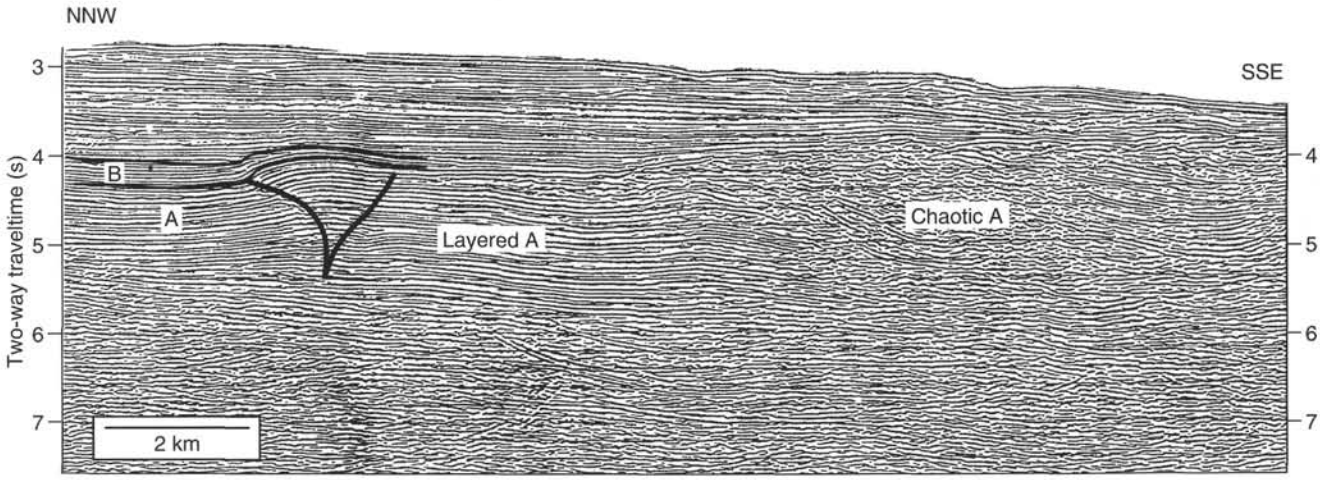

Figure 8. Section of migrated (96 channels) seismic Line MT03 on the upper Côte d'Ivoire basin (see location on Fig. 4) near the Ghanaian Platform. The section shows reverse faulting that affected both A and B units along the main continental transform.

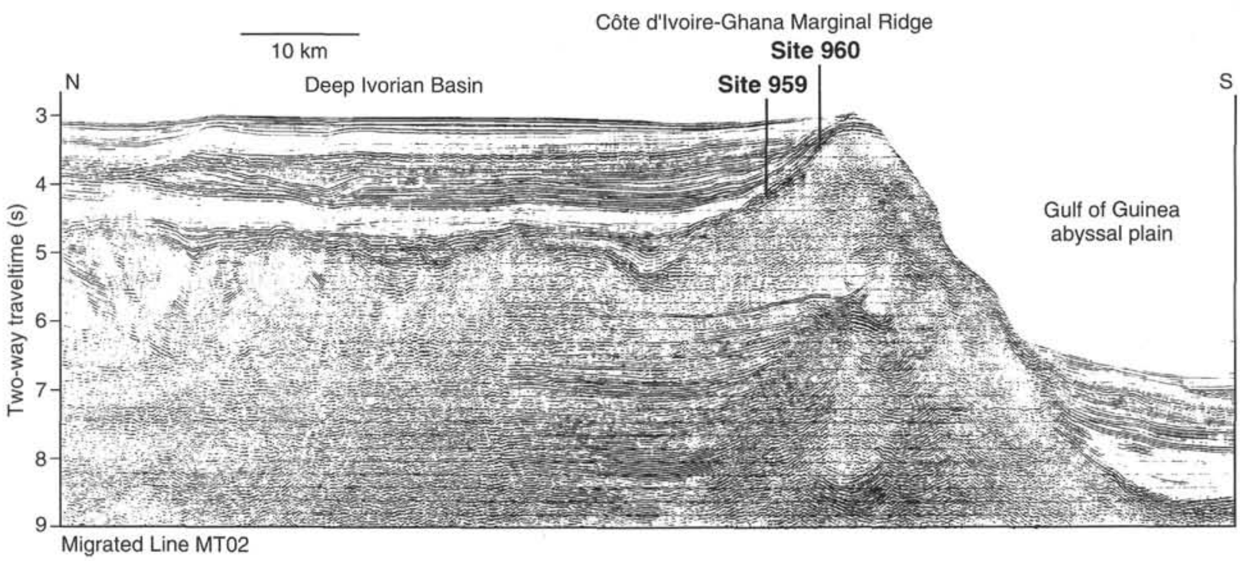

Figure 9. North-south trending, migrated (24 channels) seismic Line MT02 across the deep Côte d'Ivoire extensional basin, the bordering transform Marginal Ridge, and the adjacent oceanic Gulf of Guinea abyssal plain (see location on Fig. 4). The section illustrates the post-rift infilling of the extensional basin pinching out against the northern slope of the Marginal Ridge, and, at depth, the lower A unit (syn-rift sequence) and B unit (syn-rift but syn-transform sequence). *Equanaute* deep submersible dives (Mascle et al., 1993) EN07 through EN12 have been performed across the southern slope of the adjacent steep ridge.

tal transform faulting or during the continent-ocean transform active contact? Are these ridges made of upper mantle serpentinite bodies emplaced at the ocean-continent transition in this specific transform setting?

Seismic Stratigraphy

The seismic stratigraphy of the area has been defined on the basis of angular relationships between several well-identified acoustic units, especially along the northern slope of the Côte d'Ivoire-Ghana Marginal Ridge. We distinguish six main units in the cover, A through F (Fig. 5; Basile et al., 1993).

The relationship between basal Unit A and the underlying acoustic basement is still unclear. Unit A is deformed in both the divergent Deep Ivorian Basin and on the transform Marginal Ridge. It has been divided into subunits, A0, A1, and A2. A0 seems to be pre-rift in the whole area. A1 is syn-rift with respect to the Deep Ivorian Basin. A2 is post-rift in the Deep Ivorian Basin but appears deformed near and within the transform margin domain.

Unit B clearly corresponds to post-rift sediments and is not deformed within the transform margin. It unconformably overlies both Unit A of the Deep Ivorian Basin and the A2 (syn-transform) sequence of the transform margin.

Units C through F lie conformably on the previous ones, within and along the eastern side of the transform margin. However, they lie unconformably on Units B and A2 that constitute most of the northern Marginal Ridge slope. All units lie almost horizontally in the Deep Ivorian Basin, but progressively pinch out against the Marginal Ridge, possibly due to coeval ridge uplift.

Units C and D have been deposited both by aggradation within the Deep Ivorian Basin, through distal detrital sedimentation from the

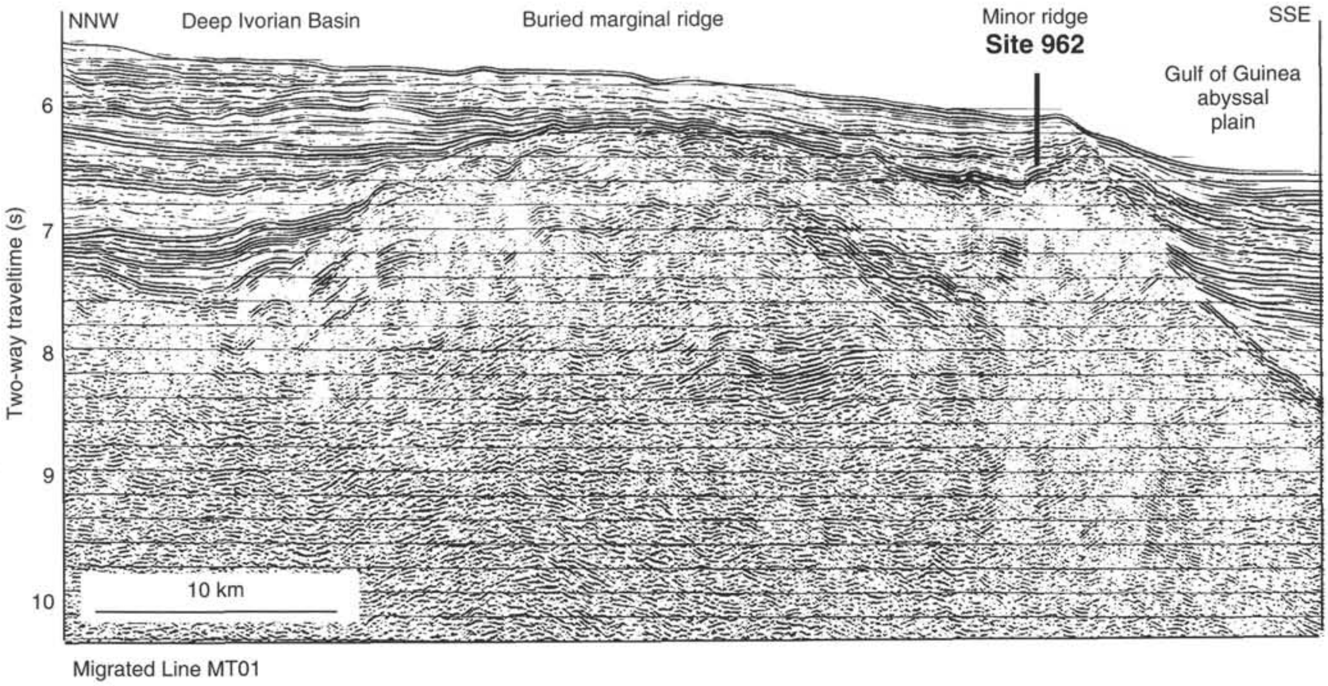

Figure 10. Section of migrated (24 channels) seismic Line MT01 (*Equasis* cruise, 1990; Mascle et al., 1995) across the buried western end of the main transform ridge and one of the en échelon minor ridges extending near the transition toward the fossil Romanche Fracture Zone (see location on Fig. 4).

African coast, and by progradation originating from the Marginal Ridge summit, in the form of proximal detrital sedimentation. Such mechanisms imply that the ridge top was near sea level at that time. The upper part of Unit C onlaps the ridge top, whereas the lower part of Unit D is restricted to the deepest part of the Deep Ivorian Basin. Such progressive restriction of the sedimentation area also characterizes Units E and F.

Lithology

Before Leg 159 only a few samples had been recovered, by coring or dredging, along the transform margin itself. These all consisted of sandstones or siltstones, but, being recovered along the southern slope of the Marginal Ridge, could not be correlated with the Deep Ivorian Basin seismic stratigraphy. During the *Equanaute* deep submersible dives, 14 geological cross sections were made along the southern slope of the Marginal Ridge, and 165 samples were collected (Mascle et al., 1994). Most of these are also terrigenous and probably belong to the same thick sandy-clayey formations (mainly sedimentary Units A1 and A2). These rocks include fine-grained to coarse-grained sandstones; greenish, lenticular to wavy-bedded siltstones; and black shales, which show numerous syn-diagenetic microfaults and slumps (Mascle et al., 1993).

Locally, near the foot of the continental slope, orthoquartzites and indurated shales, characterized by slaty cleavage, were sampled. Thin sections show recrystallized phyllosilicates, synchronous with respect to the slaty cleavage (Benkhelil et al., in press; Guiraud et al., in press a, b). Of apparent low-grade metamorphic origin, these sediments are similar to those observed in Albian deposits of the Lower Benue Basin (Benkhelil, 1986, 1988). However, the deepest *Equanaute* dive (4900 m) yielded black shales and fine-grained quartzites, comparable to Precambrian metasediments, which crop out along the nearby West African shoreline (Affaton et al., 1980). These results question the Proterozoic or Early Cretaceous age of the base of the marginal ridge.

Deep dives have likely sampled Unit A2 terranes, which would then be made of massive sandstones and siltstones interbedded with clayey beds. Direct in situ observations and sampling reveal silty-clayey strata interbedded with large-scale trough cross-bedded sandstones. Both the sedimentary facies and structures favor a very shallow marine deltaic environment (Guiraud et al., in press a, b).

Dating

Only two samples (one core and one dredge) have yet provided reliable age information on the Marginal Ridge sedimentary units. Both indicate a middle to latest Albian age (Klingebiel, 1976; L. Grosdidier, pers. comm., 1989). As both Units A1 and A2 are exposed along the slope, it is not possible to determine from which unit the samples were retrieved. Two hypotheses can be considered:

Units	Hypothesis I	Hypothesis II
E and F	Holocene through Oligocene	Holocene through Paleocene
C and D	Eocene through Late Cretaceous	Late Cretaceous through Albian
B	Cenomanian through Albian	Cenomanian through Albian
Post-transform unconformity		
A2	latest Albian	Albian
Post-rift unconformity		
A0 and A1	Albian through Early Cretaceous	Aptian through Early Cretaceous

In Hypothesis I, the samples were retrieved from Unit A1 (Blarez, 1986) and consequently this syn-rift sedimentary unit would be at least late Albian in age and conceivably older (Aptian or Neocomian, similar to other Mesozoic equatorial basins). In this case, the post-rift sediments (Units A2 and B) were deposited in latest Albian or Cenomanian times, as in the Benue Trough (Popoff, 1990), but later than sediments overlying the Aptian/Albian unconformity described in the conjugate Brazilian Margin (Zalan et al., 1985; Costa et al., 1990).

An alternative hypothesis, Hypothesis II, assigns an Albian age to Unit A2. In this case, the syn-rift unit, A1, and post-rift unconformity should be respectively Aptian and Aptian/Albian in age, as apparently indicated on the conjugate Brazilian Margin.

Because no sample was retrieved from the upper sedimentary units (B through F), they can be only tentatively calibrated by seismic cross sections with offshore boreholes located some 150 km northward of the Leg 159 drill sites on the Côte d'Ivoire shelf (Blarez, 1986).

Dating by microfauna and palynology has been attempted on a few shale samples retrieved during the deep dives. Sparse microfauna from one dive have indicated a probable Barremian to Cenomanian age (M. Moullade, pers. comm., 1994), and pollen also indicates an Early Cretaceous age (J. Dejax, pers. comm., 1994). In addition, preliminary results from fission track analysis of detrital apatites have given the following ages: 68 Ma (dive EN1, depth 3479 m), 52 Ma (dive EN4, depth 2405 m), and 44 Ma (dive EN9, depth 3905 m) for cooling below the 60°C isotherm (Bouillin et al., 1994).

Finally, tentative correlations also can be attempted between regional tectonic events and dating of the continental breakup and onset of spreading in the equatorial Atlantic. However, in this area, the lack of unambiguous magnetic anomalies prevents the determination of an accurate chronology of oceanic opening. The proposed kinematic models are thus chiefly based on fracture zone geometry and tentatively fitted to magnetic reversal chronology derived from the South Atlantic (Le Pichon and Hayes, 1971; Sibuet and Mascle, 1978; Rabinowitz and LaBrecque, 1979; Klitgord and Schouten, 1986; Cande et al., 1988; Scotese et al., 1988; Shaw and Cande, 1990; Nurnberg and Müller, 1991).

All reconstructions agree that rifting of the equatorial Atlantic occurred during the Early Cretaceous, possibly in Neocomian-Barremian time, according to Doyle et al. (1982), Popoff (1990), and Brunet et al. (1991), on the basis of geological observations in the Keta Basin and the Benue Trough. The various reconstructions also imply that the kinematics changed in Santonian times. This reorganization has been tentatively correlated with the final disruption of the African and Brazilian continental crusts within the equatorial area (Mascle and Blarez, 1987).

Tectonic Evolution of the Côte d'Ivoire-Ghana Transform Margin

From the data set presented above, and according to experimental modeling of the deformations at rift/transform intersection, Basile et al. (1992, 1993) have proposed a four-stage schematic evolution of the Côte d'Ivoire-Ghana Transform Margin.

Stage A. Early Rifting of the Deep Ivorian Basin and Shearing of Its Southern Border (Fig. 11A)

During Early Cretaceous times, the African and South American continents were in contact along their equatorial transform boundaries. The future Deep Ivorian Basin and the Ghanaian Shelf were facing their Brazilian Margin conjugates, respectively the Barreirinhas Basin and the Piaui-Ceara area.

According to plate reconstruction and geological field data (see above), opening of the equatorial Atlantic Ocean initiated during Early Cretaceous times (possibly during the Neocomian). The Deep Ivorian Basin was then created as the result of an east-west to east-northeast–west-southwest oriented extension, generating north-south half-grabens and associated tilted blocks. The sedimentary infill (syn-rift Unit A1), deposited over the whole basin, was likely thicker within the half-grabens and along the future transform margin where tectonic features were also generated.

Data from *Nautile* deep dives (Mascle et al., 1993, 1994; Guiraud et al., in press a, b) indicate that the sedimentation was mainly detrital and probably in a subaerial, deltaic to lacustrine environment. In the future transform area, detrital sedimentation was probably greatly influenced by the vicinity of the Brazilian Shelf, and was potentially controlled by rapid subsidence in structures such as pull-apart basins.

As the stretching of the Deep Ivorian Basin crust progressed, the basin deepened, and relative shear motion between the African plate and the South American plate affected its southern border. By that time, this area evolved as an accommodation zone, undergoing concurrently vertical motion between a thinning extensional Deep Ivorian Basin and the Brazilian Shelf and an increase in the intensity of horizontal (transcurrent) motion from west to east.

As expected from this kinematic model, the observed strike-slip and dip-slip motions decreased to the east and increased to the west. Early en échelon strike-slip fault zones were generated at the contact between the rifted basin and its transform boundary. Vertical displacement, especially in the western area, was recorded by tilting of the northern slope of the Marginal Ridge and coeval creation of an east-west basin perpendicular to the north-south extensional horsts and half-grabens of the still thinning Deep Ivorian Basin.

Stage B. End of Rifting and Intracontinental Transform Faulting (Fig. 11B)

Rifting ceased in the Deep Ivorian Basin when oceanic crust was created along its western edge. Continental breakup there was recorded by a post-rift unconformity and by the deposition of Unit B in the deepest parts of the main depocenters. Before this event, potential block rotation may have occurred within the Deep Ivorian Basin, reworking former extensional features in anticlinal features and strike-slip lineaments.

Along the southern border of the Deep Ivorian Basin, initiation of the drift stage induced transform-type displacement between the two continental plates. This event may have been contemporaneous with deposition of post-rift Unit A2, which is restricted to the transform margin. The deposition of Unit A2 occurred above and along the northern slope of the Marginal Ridge, and contributed to its accretion.

Before Unit B deposition, the transform motion shifted toward the south, to the top of the present continental slope where the occurrence of structural features observed on the seismic data and during deep submersible dives (sets of brittle joints, slaty cleavage, folds, and microfolds) is in good agreement with a dextral activation of N60° major faults.

Stage C. Continent/Ocean Transform Faulting (Fig. 11C)

Final continental parting between West Africa and northeastern Brazil brought into contact the newly created Gulf of Guinea oceanic crust and the continental transform fault that became, at this time, an active continental transform margin. The active transform system is thought to be located within the thin and weaker young oceanic crust. Differences in depth between the continental border and the oceanic basin could have led to gravitational sliding, creating the southern slope of the Marginal Ridge and exposing the deep Unit A; this may have led to a progressive cooling in Late Cretaceous to Paleocene times as indicated by fission track studies (Bouillin et al., 1994).

However, the contact between hot oceanic lithosphere and colder continental crust should have induced strong thermal gradients and resulted in subsequent Marginal Ridge uplift (Todd and Keen, 1989; Lorenzo and Vera, 1992). Within the Deep Ivorian Basin, coeval sedimentation (Unit D) may have recorded such an uplift, while the previous sedimentary units were tilted northward. This uplift probably increased until the passage of the oceanic spreading ridge. At this stage, the vertical motion can be estimated in the order of 1 km, 20 km north of the continent/ocean boundary. This uplift is on the same order as the thermal uplift hypothesized by Todd and Keen (1989) for the southern Newfoundland Transform Margin.

Stage D. Passive Margin Evolution (Fig. 11D)

Active tectonism along the transform margin ceased when the spreading center passed south of the Côte d'Ivoire-Ghana Margin. The transform margin and the adjacent oceanic basin then started to

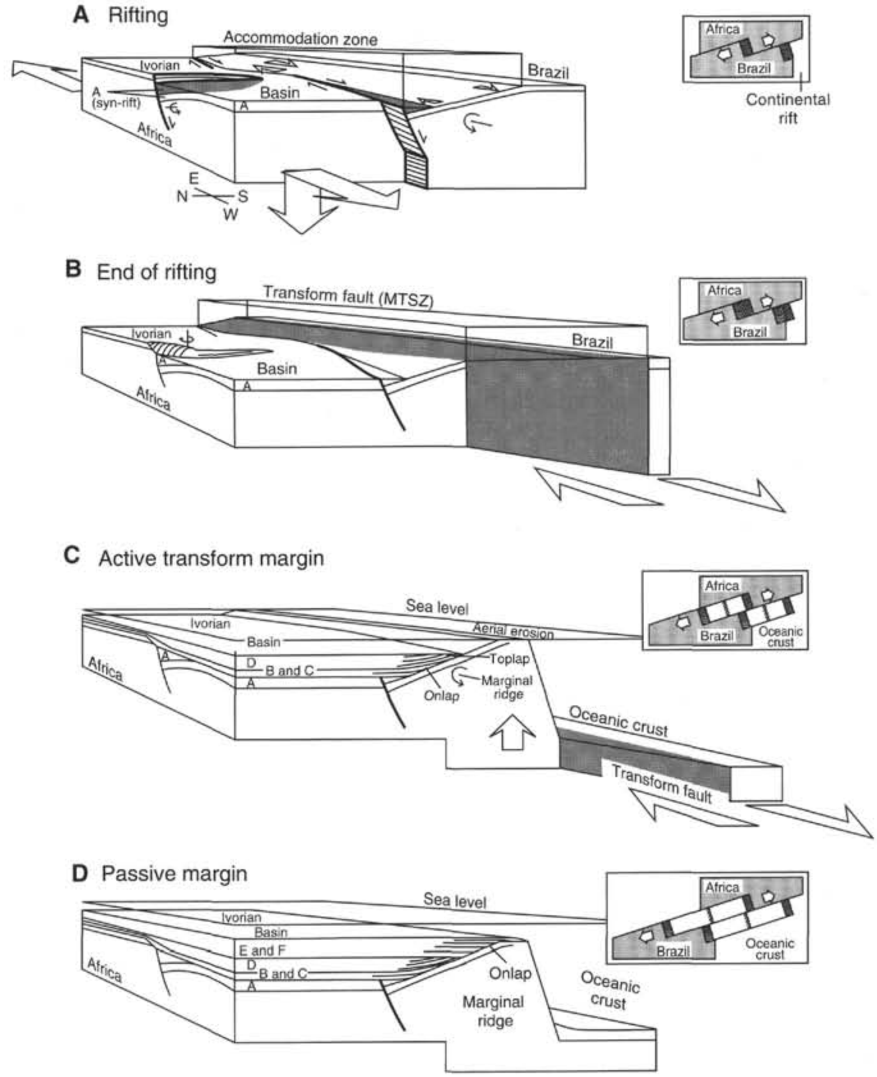

Figure 11. Four main stages in the evolution of the Côte d'Ivoire-Ghana margin (view from the west-northwest: after Basile et al., 1993). Stage A: stippled areas show syn-rift basins (divergent basins and Marginal Ridge). Stages B and C: shaded belt indicates main transform domain. Stage D: final massive margin.

subside as a result of thermal subsidence. Subsequently, the strong damming effect of the Marginal Ridge restricted most of the detrital sediment input to the Deep Ivorian Basin. The only striking feature within the subsequent sedimentary cover relates to a major Cenozoic lowstand (Oligocene, between Units E and F; Vail and Hardenbol, 1979; Haq et al., 1988). This lowstand induced strong submarine erosion, still imprinted in the present morphology by canyons and wide submarine valleys.

PETROLEUM GEOLOGY AND HYDROCARBON POTENTIAL

Côte d'Ivoire and Ghana both have commercial, albeit relatively small, oil and gas accumulations in their offshore waters. Geochemical studies to identify and characterize source-rock horizons, their petroleum potential, and degree of maturation on the continental shelf north of the study area have been performed by oil exploration companies. Due to the proprietary nature of industry investigations, detailed analytical data are difficult to obtain.

Source-rock-quality black shales on the shelf range in age from Miocene to Albian. Black shales within the Albian section contain high levels of organic matter (TOC = 0.6%–3.7%) and are thermally mature over much of the Côte d'Ivoire-Ghana continental margin. The organic matter is a mixture of marine (type II) and lesser amounts of terrestrial (type III) material. Albian source rocks are considered by the petroleum industry to have produced significant amounts of hydrocarbons. In this regard they are the most important source rock in the area.

Cenomanian and Early Senonian black shales have contributed moderate amounts of hydrocarbons. Their distribution and thickness are variable due to erosion and non deposition, though organic carbon content is high (TOC = 0.5%–2.6%). These source rocks contain marine organic matter (type II). Depth of burial frequently is insufficient for the Cenomanian and early Senonian source rocks on the shelf to have attained thermal maturity.

Campanian, Maastrichtian, Paleocene, and Miocene sediments contain sporadic black shale interbeds on the continental shelf. These shales have fair to good petroleum potential. However, due to low levels of thermal maturation, they have generated very limited amounts of hydrocarbons.

SCIENTIFIC OBJECTIVES OF LEG 159

The primary objectives for the drilling of the transform margin were to assess the sedimentary and deformation processes that are active along this specific continental borderland, as a result of the different stages of transform tectonism. Another goal of Leg 159 was to obtain a continuous upper Miocene to Pleistocene sequence of pelagic sediments to document paleoclimatic and paleoceanographic changes in the equatorial Atlantic Ocean. Finally, the potential of recovering a complete sedimentary sequence from Pleistocene to Early Cretaceous offered the opportunity to improve the biostratigraphy of the equatorial Atlantic and document the Paleogene and Cretaceous development of the gateway between the North and South Atlantic basins.

Sedimentary and Deformation Processes Active at Transform Margins

In comparison with other continental margins that also result from continental breakup, such as volcanic or divergent continental margins, transform margins display many specific characteristics, including (1) a very abrupt ocean-continent transition (on the order of a few kilometers) well-expressed bathymetrically, which should strongly constrain their thermal evolution; (2) a complex history of vertical displacement (uplift and subsidence); (3) a diachronous tectonic history, initially dominated by rifting and then followed by transform motion between two plates; and (4) high input of shallow-water sediments as a consequence of active transform tectonics and initial rapid subsidence. All these characteristics need to be constrained by evaluation of their timing, the succession of tectonic and thermal regimes, the rates and types of sedimentation, and the degree of sediment diagenesis.

1. Timing

Anticipated controls on timing concern (a) both the onset and the end of extension and of shear faulting on the margin itself, and (b) the onset of accretion within the adjacent oceanic basin. These controls were obtained at Sites 959–961, and potentially at Site 962, which recovered material for dating coeval sedimentary units (syn-rift, syn-transform, post-rift) and the different unconformities (breakup, end of transform) between units. Moreover, comparison among Sites 960–962 allowed evaluation and comparison of differences in subsidence along transform margin strike.

2. Tectonic Regimes

Definition of the tectonic regimes that successively prevailed on the transform margin was one of the crucial points to be addressed by drilling the deep parts of the section at Sites 959–962. We knew from the data already in hand (*Equanaute* samples and in situ observations) that the clastics that constitute the deeper units have recorded pre-lithification, syn-lithification, and post-lithification microstructures of syn-sedimentary and tectonic origins. How these correlated with the main episodes of margin generation and the extent to which they would allow reconstruction of both the space and time evolution of the tectonics and paleostresses were questions that we hoped to solve by continuous coring and FMS logging at all four sites.

We expected that paleomagnetic measurements would also contribute to the understanding of transform margin tectonic mechanisms. Have tectonic blocks, such as the one on which Site 961 is located, been tectonically transported or rotated? What is the significance of such motions? Have they been occurring at a margin scale, at a tilted-block scale, or are they restricted to lithologic formations or even to sedimentary displacements?

We expected that variations of subsidence and uplift through time (thermal constraints) and space (thermal and tectonic constraints) of the different transform margin structural domains could be evaluated by reconstruction of the sedimentary environment and by dating of successive sedimentary onlaps and toplaps seen on seismic lines crossing Sites 959 and 960, compared to those crossing Sites 961 and 962.

3. Sedimentation and Diagenesis

We anticipated that continuous coring and logging down to 1600 m at Site 959 would determine (a) the origin and dynamics of detrital and marine sedimentation along a transform margin border since the early tectonically active stages of margin formation (likely Early Cretaceous clastics), through the transform tectonic/thermally-controlled stages (middle Cretaceous–Paleocene open marine sediments) to the Eocene–Holocene passive stage, and (b) the degree of diagenesis and/or metamorphism to which transform margin sediments have been submitted during and after tectonic activity, and during sharp contact with a hot oceanic crust. Clay mineral recrystallization and vein fluid inclusion studies, apatite and zircon fission track dating, and organic matter maturation analysis will be used to monitor in detail the past thermal regime of the transform margin. The results will be compared to those from Sites 961 and 962 to test whether there are lateral variations due to progressive southwestward crustal thinning as expected.

4. Transform Margin–Fracture Zone Transition

It has been postulated that the 20-km-thick crust of the Côte d'Ivoire-Ghana Marginal Ridge, on which Sites 959 and 960 are located, is en échelon relayed toward the southwest (toward the fossil Romanche Transform) by minor, now sediment-buried ridges. Are these ridges, which lie on a thin crust (Moho depth 12 to 13 km; Sage, 1994) of continental or oceanic basement, made of intensively deformed sediments or of upper mantle serpentinized bodies emplaced at the ocean-continent transition near an incipient oceanic transform? We anticipated that this question could be answered by drilling 200 or 300 m into the acoustic basement at Site 962.

All data (continuous coring, logging) recovered at the three sites, particularly within the deep sedimentary sequences, and from shore-based studies, will be fundamental to a geologically well-constrained thermo-mechanical model for transform margin creation and evolution.

PALEOCEANOGRAPHIC OBJECTIVES

The paleoceanographic potential of the sites drilled during Leg 159 stems from their proximity to the Benguela Current and West African Monsoon, from their bathymetric range (extending from intermediate depths to below the sill of the eastern Atlantic basins), and from their location within an area of relatively high hemipelagic sedimentation rates. Specific objectives were to (1) characterize and infer the origin of Atlantic intermediate waters, (2) monitor the strength of the West African Monsoon and its influence on equatorial upwelling and climate, (3) monitor the strength of the Benguela Current, (4) improve the continuity and resolution of tropical Atlantic biostratigraphies, (5) determine changes in the relative importance of deep-water flux and local productivity on the character of waters in the deep Eastern Atlantic Basin, (6) recover middle Cretaceous anoxic sediments, and (7) determine the timing and geometry of the Cretaceous Atlantic Gateway.

1. Character and Origin of Atlantic Intermediate Waters

At a depth of 2100 m, Site 959 lies within intermediate and uppermost deep waters. Benthic foraminifers collected from this site were expected to record, in their species composition and shell chemistry, the properties of these water masses. Studies elsewhere (Curry et al., 1988; Duplessy et al., 1988; Raymo et al., 1989; Oppo et al., 1995) suggest that over the last several million years the character of the Atlantic's deep and intermediate waters has varied as the transition between northern and southern source waters has moved north and south, and as their vertical distribution has reversed.

There is direct evidence that the amplitude of the north-south movement of southern source waters flowing into the deep western Atlantic has increased over the last several million years (Raymo et al., 1989). Evidence for reversal of the vertical distribution of northern and southern source waters is well-documented for the latest Pleistocene (Curry et al., 1988; Duplessy et al., 1988), but for the longer term the evidence is indirect. A record from the Caribbean (Oppo et al., 1995) is assumed to reflect the character of intermediate waters flowing over a sill. Thus we anticipated that Site 959 would provide a more direct record of intermediate water properties, for both a longer period of time and at greater time resolution. Site 959 also was expected to provide a record upstream of southern source intermediate waters and downstream of northern source waters relative to the Caribbean record, helping to constrain potential sources of the intermediate waters flowing between them.

2. Strength of the West African Monsoon and Its Influence on Equatorial Upwelling and Climate

The West African Monsoon is driven by seasonal land-sea temperature differences. It influences upwelling along the West African coast and the transfer of moisture into the continental interior. The strength of this system is expected to have increased with the decreasing temperatures and increased temperature gradients through the late Cenozoic. The high sedimentation rates expected at Site 959 and its close proximity to the West African Monsoon were expected to offer a record of its long-term evolution and of the amplitude of its local effect on upwelling and climate.

3. Strength of the Benguela Current

The Benguela Current forms the warm and salty portion of the shallow return flow that balances the export of North Atlantic Deep Water. The other portion of the return flow, carried by the Antarctic Intermediate Water, is relatively cold and fresh. As noted by Gordon (1994), the relative volumetric contributions carried by these two routes largely control the meridional flux of heat and moisture into the North Atlantic and, therefore, influence the ocean's main thermohaline circulation. This is a potential means by which Southern Hemisphere processes could control the formation of northern source deep waters. Using the chemistry and species compositions of benthic and planktonic foraminifers at Site 959, we considered it possible to monitor the relative flux of waters returning northward as either warm and salty Benguela Current waters or cold and fresh Antarctic Intermediate waters.

4. Tropical Atlantic Biostratigraphy

The combination at Site 959 of relatively high sedimentation rates, stratigraphic continuity, and proximity to sources of pelagic and hemipelagic sediments was expected to allow refinement and correlation of tropical marine and palynological biostratigraphies.

A major gap in our knowledge of Neogene stratigraphy is a well-dated tropical/warm subtropical biostratigraphy for the middle Miocene. Although numerous fossiliferous sequences have been drilled (Legs 115, 130, 154), none of these has recovered cores with both well-preserved microfossils and a good magnetochronology. The absence of a well-dated tropical/warm subtropical biostratigraphy is unfortunate because the middle Miocene was a period of rapid expansion of the Antarctic ice sheet, and it marked the initiation of the modern style of deep-water formation in the North Atlantic. Understanding these events is hampered by difficulties in comparing events between the tropics and the high latitudes. Because of its shallow location in an area of high hemipelagic sedimentation, Site 959 offered the opportunity to recover well-preserved, high-resolution magnetic and biostratigraphic records.

5. Relative Importance of Deep-water Flux and Local Productivity on the Character of Waters in the Eastern Atlantic Basin

The character of waters in the deep basins of the eastern Atlantic Ocean is determined by the local modification of waters that originate in the western Atlantic and then flow over sills through Mid-Atlantic Ridge fracture zones. Changes in the character of deep waters in the western Atlantic, their flux into the eastern basins, the flux of organic matter from surface waters, and, on longer time scales, the depth of the fracture zones can all be expected to change the character of the deep waters in the eastern Atlantic (e.g., Curry and Lohmann, 1983). We felt that comparison of sediments and benthic foraminifer chemistry from the deep Site 962 with those from the shallower Sites 959 and 960, as well as from sites drilled during Leg 154 on the Ceara Rise (Curry, Shackleton, Richter, et al., 1995) in the western Atlantic, would allow determination of the relative importance of these different influences on sediment character and water chemistry in the deep eastern Atlantic.

6. Recovery of Middle Cretaceous Anoxic Sediments

We anticipated that Site 959 would penetrate laminated, organic-rich sediments deposited from anoxic bottom waters. The location of the site, in the central Atlantic Ocean, afforded the opportunity to examine the temporal evolution of bottom-water oxygen conditions as tectonism transforms the region from a restricted rift basin environment to fully oxygenated hemipelagic conditions. This transformation is of global interest because the opening of the central Atlantic likely played an integral role in ventilation of the South Atlantic Ocean in the middle to Late Cretaceous. Past interpretations of the global distribution of anoxic sediments have been controversial. Some have proposed periods of global ocean anoxia (Jenkyns, 1980); others have argued for local anoxia in deep local basins (Waples, 1983) and expanded oxygen minimum zones due to sluggish Cretaceous deep-water circulation (Bralower and Thierstein, 1984). More recent investigations (Herbert et al., 1986; Oglesby and Park, 1989) have also argued that much of the cyclic character of Cretaceous anoxia is the product of orbital forcing. Given the fundamental role that opening of the central Atlantic must play in ventilation of the South Atlantic, we anticipated that recovery of anoxic middle Cretaceous sediments would better constrain existing models of Cretaceous anoxia.

The elements rhenium (Re) and osmium (Os) are enriched in anoxic sediments at the time of their deposition (Ravizza et al., 1991). This enrichment opens the possibility of applying the decay of ^{187}Re to ^{187}Os as a chronometer to determine the time of deposition of these sediments (Ravizza and Turekian, 1989). Because the majority of the Os in these sediments is derived from seawater, the initial Os isotopic composition of anoxic sediments effectively records the Os isotopic composition of seawater at the time of deposition (Ravizza and Turekian, 1992). These characteristics of the Re-Os system open the possibility of using initial Os isotope ratios of Cretaceous black shales and organic-rich Eocene and Oligocene diatomites to reconstruct the Os isotopic composition of Cenozoic and Cretaceous seawater. Work to date suggests that the Os isotopic evolution of seawater, like the seawater Sr isotope record, has potential application as a stratigraphic tool and a paleoceanographic tracer (Pegram et al., 1992; Ravizza, 1993). Conducting a Re-Os study of middle Cretaceous black shales recovered during Leg 159, in conjunction with analyses of middle Cretaceous shales from existing ODP and DSDP material, will allow us to determine whether the middle Cretaceous oceans were well mixed with respect to Os isotopic composition. We anticipate that local restricted basins maintained distinct Os isotope signatures until rifting and concomitant ventilation shifted Os isotope ratios to open ocean values.

7. Timing and Geometry of the Cretaceous Atlantic Gateway

The sedimentary record from Sites 959 and 960 have better constrained the history and conditions of the equatorial connection between the North and South Atlantic oceans. In particular, the drilling results have helped to determine (a) the age of the gateway (potentially as far back as the Aptian-Albian), (b) the nature of the gateway (an Atlantic gateway vs. a gateway crossing Africa through the Sahara and the Benue Trough), and (c) the bathymetric evolution of the area.

The same sites have helped determine the middle (Albian) and Late Cretaceous paleoenvironmental evolution, constraining (a) the age and nature of the first marine sedimentation, (b) the evolution of paleoenvironments (bathymetry, salinity, oxygenation, surface and bottom circulation, upwellings) and biofacies (Atlantic or African gateway) during the middle and Late Cretaceous, (c) the initiation of open marine environment and communication with the open ocean (possibly from Albian times onward), (d) the initiation of cold-water deep currents originating from the south ("paleo-Benguela current") and influence on the productivity and dissolution of carbonates, (e) the geographic extent of the anoxic event (black shales) at the Cenomanian/Turonian boundary (e.g., Jenkyns, 1980), (f) the origin of sedimentary onlaps and toplaps along the northern slope of the Côte d'Ivoire-Ghana Marginal Ridge: whether they are due to tectonic events (uplift or subsidence of the Marginal Ridge) or environmental variations (in sedimentation rate, sedimentary source currents, sea level); and (g) the record of Cenozoic global climatic events in an area influenced by deep-water circulation along the Romanche Fracture Zone.

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