OCEAN DRILLING PROGRAM

LEG 159 SCIENTIFIC PROSPECTUS

THE COTE D'IVOIRE - GHANA TRANSFORM MARGIN
EASTERN EQUATORIAL ATLANTIC

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ABSTRACT

Drilling at transform continental margins has received attention for two reasons. Firstly, transform faults represent the third category of major plate boundaries, but are still less understood than the two other major plate boundaries, divergent and convergent. Among transform faults, transform continental margins are still poorly known, and have never been investigated by the potentialities of scientific drilling. Secondly, drilling at a transform margin can constrain the structure and evolution of the ocean-continent transform boundary, particularly deformational history, vertical movements, and their effects on the sedimentary records.

Leg 159 will investigate the Côte d'Ivoire-Ghana (CIG) Margin in the eastern equatorial Atlantic, one of the best known examples of a former transform boundary between continental and oceanic crusts. The margin has been created by major transform motion between the plate boundaries and, since its creation, the CIG Margin has not experienced any major regional tectonic disruption; its present-day sedimentary and tectonic features are thus directly inherited from its Cretaceous transform margin history.

Drilling three sites, Leg 159 will document 1) the development of the transform margin and particularly the relationship between deformation and sedimentation; 2) the nature, structure, and deformation history of such transform boundary; 3) the history of the oceanic gateways between the Central and South Atlantic during the opening of the Equatorial Atlantic, particularly during the Cretaceous; and 4) Cenozoic paleoceanographic and climatic history of the central eastern Atlantic.

INTRODUCTION

The concept of a transform (or sheared/translational) continental margin as a specific type of continent/ocean boundary progressively developed since the 1970's. Geophysical results from several transform margins clearly demonstrate that these continental borderlands are drastically different from divergent margins, on the basis of crustal structure, deformation, subsidence, and sedimentation history.

Within the past 20 years, several marine geophysical cruises (mainly gravimetry, refraction, and reflection seismic profiling) have been devoted to a few transform margins, namely a) Agulhas

Margin and its conjugate, the Falkland Margin (Ewing et al., 1971; Emery et al., 1975; Scrutton, 1976, 1979, 1982; Lorenzo and Mutter, 1989); b) southern Newfoundland Margin (Hayworth and Keen, 1979; Todd et al., 1988; Keen et al., 1990); c) southern margin of the Exmouth Plateau (Lorenzo et al., 1991); d) Spitzbergen Margin (Lowell, 1972; Eldholm and Talwani, 1982; Eldholm et al., 1987); and e) 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, Auroux, et al., 1989; Basile, 1990; Basile et al., 1992; Mascle et al, 1993; Basile et al., 1993) and their conjugate, the northern Brazilian Margin (Ponte and Asmus, 1978 ; Zalan et al., 1985 ; Costa et al., 1990). Scientific drilling was conducted adjacent to transform margins during DSDP Leg 36 (Barker, Dalziel et al., 1976) and ODP Leg 114 (Ciesielski, Kristofferson, et al., 1988) in the Falkland area and ODP Leg 122 in the Exmouth Plateau (Haq, von Rad, O'Connell, et al., 1990).

From these results, three main morpho-structural features of the transform margin (e.g., CIG Transform Margin (Figs. 1a, 1b, and 1c) can be recognized, namely the existence of a) lateral structural continuity between a major oceanic fracture zone and a continental transform margin (the Romanche Fracture Zone and CIG Margin); b) a very steep and narrow continental slope (20-30 km) between a continental shelf and an adjacent oceanic abyssal plain, indicating a very sharp crustal transition between thick or partially thinned continental crust and oceanic lithosphere; and c) a morphologically well-expressed marginal ridge, bounding the transform margin, along an adjacent extensional basin (Côte d'Ivoire Basin).

All these features result from a translational stress acting between two continents along active transform faults. During rifting and opening, such evolution can be schematically represented as three main stages (Figs. 2a and 2b) (Mascle and Blarez, 1987).

Stage 1 - An intra-continental active transform fault (Stage A on Fig. 2a), resulting in contact between two thick continental plates of variable thicknesses. In this case, the transform boundary of the extensional basin undergoes shear stresses and accompanies potential uplift to create a bordering marginal ridge (Fig. 2a).

Stage 2 - Continent-ocean active transform fault contact (Stage B on Fig. 2a). In this setting, the proximity of the hot oceanic lithosphere may induce important vertical readjustment of the nearby continental margin border (Fig. 2a).

Stage 3 - Inactive continent-ocean transform fault (Stage C on Fig. 2a). Tectonically, this is a passive transform margin experiencing relatively homogeneous thermal subsidence (Fig. 2a).

On a tentative 3-dimensional view sketch (Fig. 2b), such evolution implies successive crustal/lithospheric contacts that should have led to strong thermal and pressure contrasts that may have been recorded during the margin creation and subsequent evolution (Sage, 1994).

Leg 159's objectives are to

1) determine the exact tectonic and sedimentary processes that are involved in the creation of the different main morpho-structural features generated at the CIG Transform Margin, including the formation of the marginal ridge and the nature and structural deformation of the acoustic basement underlying the ridges generated at the transform boundary;

2) document the type of deformation (and deformation history) of the CIG Transform Margin during its successive stages of evolution;

3) constrain the timing, rate, and degree of vertical motion (subsidence and uplift) occurring on the CIG Transform Margin;

4) investigate the relationship between the thermal evolution of a transform margin and the actively spreading oceanic crust, including sediment diagenesis within the environs of the transform margin and the heating, hydrothermalism, and possibly magmatism occurring in response to the nearby spreading center that progressively migrated along, and then away from, the transform margin;

5) collect crucial data on the history of the oceanic gateways across the Equatorial Atlantic and on the sedimentation of specific facies during the opening phase.

6) document the paleoceanographic and climatic evolution of the eastern equatorial Atlantic during the Cenozoic.

REGIONAL GEOLOGY OF THE COTE D'IVOIRE-GHANA TRANSFORM MARGIN

The CIG 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 particular recent investigation along this margin is the Côte d'Ivoire Marginal Ridge, which corresponds to a transition between a laterally thinned continental crust and an 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 (Fig. 1c).

The seismic stratigraphy and tectonics (Fig. 3) of the area to be drilled during Leg 159 are chiefly based on investigations by the 1983 *Equamarge I* cruise (Blarez, 1986; Blarez et al., 1987; Mascle and Blarez, 1989; Mascle et al., 1988), the 1990 *Equasis* cruise, the *Equaref* cruise and *C. Darwin* cruise 55 (1990 and 1991, respectively), the 1988 *Equamarge II* cruise (Mascle, Auroux, et al., 1987; Basile et al, 1989; Popoff et al., 1989; Pontoise et al, 1990; Basile, 1990; Basile et al., 1992; Basile et al., 1993), the 1992 *Equanaute* cruise (Mascle et al., 1993 and 1994), and a few results from the Brazilian conjugate margin, explored by PETROBRAS (Ponte and Asmus, 1978; Zalan et al., 1985; Costa et al., 1990).

Seismic Stratigraphy

The seismic stratigraphy is defined on the basis of angular relationships between several sedimentary units, especially along the northern slope of the CIG Marginal Ridge. Six main units, A to F (Figs. 4 and 5), can be distinguished in the cover (Basile et al, 1993).

The relationships between basal Unit A and the underlying acoustic basement is still not clear. This unit is deformed in both the divergent Ivorian Basin and 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 in the divergent Ivorian Basin. A2 is post-rift in the Ivorian Basin, but appears deformed within the transform margin domain.

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

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

Sedimentary units C and D have been deposited both by aggradation within the Ivorian Basin (i.e., distal detrital sedimentation from the African coasts) and by progradation originating from the marginal ridge summit (i.e., proximal detrital sedimentation). Such mechanisms imply that the ridge top was near sea level at that time. The upper part of the C sequence onlaps the ridge top, whereas the lower D sequence is restricted to the deepest part of the Ivorian Basin. Such progressive restriction of the sedimentation area also characterizes the E and F sequences.

Lithology

To date, only a few samples have been recovered by coring or dredging along the transform margin itself. All of these samples consist of detrital sediments (sandstones or siltstones) but unfortunately could not be correlated with the seismic stratigraphy. However, during the *Equanaute* dives, 14 geological cross sections were made along the southern slope of the marginal ridge, and 165 samples were collected (Mascle et al., 1994) (Fig. 6). Most of these samples 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 syndiagenetic microfaults and slumps (Mascle et al., 1993).

Locally, near the foot of the continental slope, orthoquartzites and indurated shales were sampled. These shales are characterized by slaty cleavage, and thin sections show recrystallized phyllosilicates, which are synchronous with respect to the slaty cleavage. This recrystallization, of probable low-grade metamorphic origin, is rather similar to that observed in Albian deposits of the Lower Benue Basin (Benkhelil, 1986, 1988). However, the deepest dive (4900 m, dive 11) has also yielded black schists and fine-grained quartzites comparable to metasediments of early Voltaian age (Precambrian), which crop out along the nearby West African shoreline (Affaton et al, 1980). These results cast doubt on the Proterozoic or Early Cretaceous age of the base of the Ridge.

In our opinion, *Equanaute* dives have chiefly documented the A2 unit of massive sandstones and siltstones interbedded with pelites. Here, direct in situ observations reveal silty-clayey strata interbedded with large-scale trough cross-bedded sandstones. Both the sedimentary facies and structures favor a very shallow marine environment of deltaic type.

Only a few samples (chiefly collected during dive 14) can be related to the uppermost units D through F. These samples consist of clayey limestones, dolomites, and siltstones.

Age

Only two samples (one core and one dredge) have yet provided reliable age information on the sedimentary units. Both samples indicate a middle to uppermost Albian age, one dated by palynology (Klingebiel, 1976) and the second by Ostracoda (E. Grosdidier, pers. comm., 1989). Since both the A1 and A2 sedimentary units are exposed along the slope, it is not possible to determine from which unit the samples were retrieved. Two hypotheses can be considered.

Units	Ages following hypothesis I	Ages following hypothesis II	
F	Present to	Present to	
E	Oligocene	Paleocene	
D	Eocene to	late Cretaceous	
C	late Cretaceous	Albian	
B	Cenomanian to	Albian	post-transform unconformity
A2	latest Albian	Albian	post-rift unconformity
A1	Albian to	Aptian	
A0	Early Cretaceous	Early Cretaceous	

In hypothesis I, the samples were retrieved from Unit A1, according to Blarez (1986). From this hypothesis, we infer that syn-rift sedimentary Unit A1 is at least late Albian in age and possibly older (Aptian, as are all the equatorial basins, or even Neocomian). In this case, the post-rift sediments (A2 and B units) were deposited in latest Albian or Cenomanian times, as in the Benue Trough (Popoff, 1990), but later than 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 the A2 unit. In this case, the syn-rift unit, A1, and post-rift unconformity should be Aptian and Aptian/Albian in age, respectively, as apparently indicated on the conjugate Brazilian Margin.

Since no samples were retrieved from the upper sedimentary units (C and F), these units must be tentatively dated from the hypothetical basement age and through calibration to an offshore borehole located 150 km northward on the Ivorian shelf (IVCO2, Fig. 1c) (Blarez, 1986).

Since the samples retrieved during the dives consist mainly of sandstones, no easy dating by microfaunas could be expected. Tentative dating by microfauna and palynology has been attempted on a few shale samples. A few microfauna from the *Equanaute* dive 1 indicated a probable Barremian to Cenomanian age (M. Moullade, pers. comm., 1994); pollens indicate an early Cretaceous age (J. Dejax, pers. comm., 1994). Preliminary results from the fission track of detrital apatites give the following ages of cooling for crossing the 60°C isotherm: 68 Ma (dive EN1, depth 3479 m), 52 Ma (dive EN4, depth 2405 m), and 44 Ma (dive EN9, depth 3905 m) (Bouillin et al., 1994).

Tentative correlations can also be made between the main regional tectonic events and the dating of the oceanic opening of 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; Scotese et al., 1988).

All reconstructions agree that rifting of the Equatorial Atlantic occurred during the Early Cretaceous, possibly in Neocomian-Barremian time in the Keta Basin (Doyle et al., 1982) and the Benue Trough (Popoff, 1990; Brunet et al., 1991). The various reconstructions also imply that kinematic parameters were modified in Santonian time. This reorganization has tentatively been correlated with the final disruption of the African and Brazilian cratons within the equatorial area (Mascle and Blarez, 1987).

Tectonics

To the north of the marginal ridge, the deep Ivorian Basin is an extensional margin, thinned by dip-slip faults trending north-south to northeast-southwest. These faults bound tilted blocks and half-grabens, which are infilled by thick syntectonic sediments (Unit A1; Fig. 4). To the south, the fossil marginal ridge is a 130-km-long and 25-km-wide prominent feature that towers 1300 m over the Ivorian Basin and more than 4000 m over the adjacent oceanic crust (Figs. 1, 3, and 7).

The regional structure of the transform margin is linked to the westward thinning of the adjacent divergent basin (Figs. 1 and 7). 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 Ivorian Basin (Fig. 3).

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 this pseudo-basement.

East of 2°10'W (line MCS MT3, Fig. 8), transform motion has generated flower structures at the Ivorian Basin - transform margin transition. To the north, these strike-slip faults become transpressional and exhibit reverse slip. The associated en échelon folds indicate right-lateral movement (Fig. 7). To the south, there is a wide (>10 km) and deep (1 km) channel that may represent an infilled intracontinental transform valley, such as the Jordan Valley in the Dead Sea transform. The southern limit of this valley is probably near the top of the actual southern continental slope, where the deformation observed during the scientific *Equanaute* dives are more important (folding, vertical fracturing, fracture cleavage) than southward, out of the transform valley (strata tilted southeast).

Strike-slip fault activity is recorded by the sedimentation of the A1, A2, and B units. The reverse strike-slip faults were active from deposition of the A1 sequence (uplifted during the sedimentation), up to the deposition of A2 (cut by faults). An additional uplift of the A2 sequence is sealed as strike-slip faulting by the undeformed B unit (Fig. 8a).

The transform valley also was probably active during A1 and A2 deposition. Here the A1 unit is eroded and the valley is infilled by the A2 sequence, showing thick lenticular bodies prograding to the south.

Between 2°10'W and 2°45'W (MCS line MT2, Figs. 7 and 8b), along a northwest cross section of the marginal ridge, three tectonic domains can be distinguished, including the western prolongation of the transform valley observed eastward (see above). The transform valley is located at the boundary between the deep Ivorian Basin and the marginal ridge. The feature has eroded the deepest unit (A0) and is infilled partly by the faulted A1, and mainly the unfaulted A2, units. The northern marginal ridge slope is formed by an important thickening of the A2 unit to the south. This thickening results in the edification of a swell. At the top of this swell, sedimentary lenses prograde to the north, and distal fans occur along its northern slope.

To the north, the presence of the deep Ivorian Basin and the apparent northward progradation indicate that the detrital material originated from the Brazilian Shelf which, at that time of intracontinental transform faulting, was located just southward. *Equanaute* dives tend to substantiate the idea that deformation (fracturing and folding) increases upslope toward the ridge top where strike-slip activity was probably concentrated.

The seismic lines (Figs. 5 and 8b) also show that the B unit is restricted to the deep Ivorian Basin and northern ridge slope. Thus, sedimentation proceeded simultaneously by both aggradation in the Ivorian Basin (sediments originating from African coasts) and progradation (sediments probably derived from erosion of the ridge top). Units C through F are also restricted to the 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 acoustic ridges (Figs. 7 and 9) that tower over the oceanic crust to the south and over a thick (about 2 km) syn-transform basin to the north. The origin of these ridges is probably associated with transform motion, but different hypotheses can be made about their nature and deformation history. Are these ridges continental or oceanic, basement or sediments? Did these ridges appear during the rifting of the Ivorian Basin, during intracontinental transform faulting, or during the continent-ocean transform faulting?

A second question relates to the similarity between these lower margin minor ridges and en échelon ridges mapped to the west, along the inactive Romanche Fracture Zone (Honnorez et al., in press). Are these similar in nature and origin? If so, this indicates that parts of the continental margin basement (and cover) were tectonically displaced during transform motion (during, and even after, intracontinental transform contact).

Tentative Evolution of the CIG Transform Margin

From the data set already presented, and according to experimental modeling of deformation at the rift-transform intersection (Basile et al., 1992), Basile et al. (1993) proposed the following schematic evolution of the CIG Transform Margin (Figs. 10 and 11).

Initial Setting (Fig. 10)

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

Early Rifting of the Deep Ivorian Basin (Fig. 10)

According to plate reconstruction and geological field data, opening of the Equatorial Atlantic Ocean began during Early Cretaceous time (possibly during the Neocomian). The deep Ivorian Basin was then initiated 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 thicker within the half-grabens and along the future transform margin.

Data from *Equanaute* dives indicate that sedimentation was chiefly 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.

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

As the stretching of the 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 had evolved as an accommodation zone (Fig. 6), concurrently undergoing vertical motion between a thinned Ivorian Basin and the stable 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 and increased, respectively, from east to west. The first 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 ridge and coeval creation of an east-west syn-rift basin perpendicular to north-south extensional structures of the Ivorian Basin.

In this hypothesis, the accommodation zone activity is necessarily coeval with deposition of the syn-rift unit, A1, in both the Ivorian Basin (tilted blocks) and in the transform zone where detrital sediments coming from Brazil led to the development of a sedimentary wedge. Furthermore, the minor ridges were probably created during this time interval.

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

Rifting ceased in the Ivorian Basin when oceanic crust was created along its western edge. Continental breakup there was recorded by a typical 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 into anticlinal features and strike-slip lineaments.

Along the southern border of the 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 the 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 construction.

Before deposition of Unit B, transform motion shifted southward to the top of the present continental slope, where the different structural features observed during *Equanaute* dives (sets of brittle joints, slaty cleavage, folds, and microfolds) agree well with a dextral activation of N60 major faults.

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

Final continental parting between West Africa and northeast Brazil brought into contact the Gulf of Guinea oceanic crust and the continental transform fault into contact. At this time, the transform fault became an active continental transform margin. The active transform system is thought to be located within the thin oceanic crust. Differences in depths between the continental border and the oceanic basin could have led to gravitational sliding, progressively creating the southern slope of the marginal ridge.

Moreover, 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 Ivorian Basin, coeval sedimentation (D sequence) recorded such an uplift, while the previous sedimentary units were tilted northward. This uplift probably increased until the passage of the oceanic spreading center. At this stage, the vertical motion is estimated to have been on the order of 1 km, 20 km north of the continent/ocean boundary. This uplift is comparable to the thermal uplift estimated and reported by Todd and Keen (1989) for the southern Newfoundland Transform Margin.

Passive Margin Evolution (Fig. 11, Stage D)

Active tectonism of the transform margin ended when the southern spreading center passed south of the CIG Margin. The transform margin, and the adjacent oceanic basin, started to subside as a result of thermal subsidence. Afterward, 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 stage, between the E and F units) (Vail and Hardenbol, 1979; Haq et al., 1988). This lowstand induced strong submarine erosion, which is still imprinted in the present morphology by canyons and wide submarine valleys.

Alternate Reconstructions

The evolution proposed above explains the buildup of the marginal ridge by successive tilting and sedimentary processes, namely tectonic tilting during the rifting of the Ivorian Basin, thermal tilting during the continental-oceanic transform faulting, and sedimentary accretion mainly during the rifting of the Ivorian Basin. However, the relative importance of these phenomena cannot be easily determined from the available data; other potential mechanisms that will be tested by drilling are 1) marginal ridge uplift by shearing in a transpressional setting; 2) marginal ridge uplift by block tilting along the transform boundary, like transverse ridges in the active oceanic transform faults; 3) the possibility that the marginal ridge is a continental block, not thinned by the opening of the Ivorian Basin but translated from the west to its southern boundary (in this case, deformation is not expected within the block but only along its borders); 4) the marginal ridge resulted from rotations (about a vertical axis) along the transform area, which may explain both the transtensional and transpressional features that are observed eastward and westward, respectively, along the ridge (this hypothesis can be tested by paleomagnetic measurements); or 5) the marginal ridge represents a sedimentary wedge that only resulted from accumulation of detrital sediments and modeling by erosional and gravitational processes (in this case, no tectonic deformation but typical sedimentary features are expected in the drilled cores).

SCIENTIFIC OBJECTIVES

The main questions to be addressed by drilling proposed sites IG-1, IG-2, and IG-3 relate to the age, nature, and deformation of the CIG Marginal Ridge sediments and basement, and to their vertical behavior. The final objective is, of course, to understand sedimentary, structural, and thermal factors operative at transform margins. These parameters will permit a precise analysis of the tectonic and sedimentary processes involved in creation and evolution of a transform margin, and will enable better constraints on the succession of events and thermo-mechanical models.

Timing Controls and Evolution of the Sedimentary Cover

Dating of the samples collected on the *Equanaute* '92 dives is difficult, and, furthermore, these dates would pertain only to the discontinuous sedimentary units that are deeper than those expected at proposed sites IG-1 and IG-2 on the marginal ridge. No samples are yet available from the minor ridges (proposed site IG-3). Drilling is essential to provide a continuous sedimentary record, including the clayey beds (where microfauna and/or pollen are to be expected) that were not sampled during dives.

The different timing controls expected from drilling holes include evidence relating to

1) the beginning of extension in the adjacent rifted Ivorian Basin, which will be provided by sampling of the post-rift sediments, units A2 and B, at proposed site IG-1;

2) the beginning of oceanic accretion (south of the transform margin), coeval with the end of tectonic activity on the margin; this age cannot be obtained directly using the proposed sites but may be derived by dating the end of the tectonic activity on the continental margin at proposed sites IG-1, IG-2, and IG-3;

3) the initiation of shear faulting on the transform margin. Such timing can be obtained directly at proposed sites IG-2 and probably IG-3, since both sites are located near a strike-slip fault and on an assumed sheared block. Timing the end of strike-slip activity is expected from data at the three proposed sites, IG-1, IG-2, and IG-3;

4) the age of the A1/A2 unconformity, associated with the end of strike-slip faulting and related uplift, to be addressed at proposed site IG-2.

Furthermore, comparisons between sites will enable

1) correlation between the subsidence history of the margin (proposed sites IG-1, IG-2, and IG-3) and the main tectonic events (e.g., extensional rifting, continent-continent transform faulting, continent-ocean transform faulting, passive transform margin);

2) examination of the respective deformation history of both the rifted basin and of its transform boundary (proposed sites IG-1 and IG-2);

3) estimates of diachronism between the sedimentary and tectonic events along the transform margin (proposed sites IG-1, IG-2, and IG-3).

Evolution of Sedimentation and Diagenesis

Continuous coring at all three sites will determine

1) the ages and facies of the sedimentary cover, especially the post-rift sedimentary sequences (units B to D, proposed site IG-1), which are needed to construct a depth/age curve (i.e., a subsidence history of the margin);

2) the origin of detrital sediments (units B to D), derived from either north (Africa), or from south (erosion of the marginal ridge top at proposed site IG-1);

3) the origin of onlaps and toplaps detected on the northern CIG Marginal Ridge slope (proposed site IG-1). Are the onlaps and toplaps related to tectonic or isostatic events (uplift or subsidence of the marginal ridge)? Or to environmental fluctuations (e.g., sedimentation rate, currents, sea level) in proximal or distal fans?

4) sedimentation within an active transform margin, including the dynamics of detrital sedimentation in a deltaic environment, the origin of the major unconformity, and the control exerted by tectonic processes;

5) the potential diagenesis of detrital sediments in the transform margin during, and after, tectonic activity, paying particular attention to the evolution of organic matter in relation to diagenesis, metamorphism, and heating in the vicinity of an oceanic lithosphere; this study will help to constrain any thermo-mechanical model for the margin;

6) the history of water depth during marginal ridge formation; this facet of investigations will be concentrated near the top of the sequence at proposed site IG-1, and along the western extremity of the marginal ridge at proposed site IG-2; comparison between the two sites should indicate if the ridge has been uplifted after sedimentary deposition.

Finally, the Leg 159 program will investigate the nature of the bordering minor ridges at proposed site IG-3. If these ridges are similar to ridges within the fossil Romanche Fracture Zone, metasandstones are expected. Should this be the case, to understand the mechanisms that have created these lowermost-margin en échelon ridges, we need to constrain the timing of sedimentation, the depositional environment, the timing of metamorphism, and the degree of deformation.

Structural Measurements

Structural analyses are an important part of the Leg 159 drilling program, and should document

1) the type of deformation related to strike-slip activity at proposed sites IG-1, IG-2, and IG-3; according to the *Equanaute* dives, this may include microfolds, fractures, faults, and shear zones;

2) the paleostresses from small-scale tectonic features at proposed sites IG-1, IG-2, and IG-3 recorded in structural changes within the transform margin; the relative roles of strike-slip faulting and gravitational instabilities on the stress field are particularly important to evaluate the influences of those processes on formation of the marginal ridge; furthermore, metamorphism could be expected as a consequence of large-scale shearing (shear heating) that has probably generated the en échelon pattern of ridges;

3) the importance of gravitational deformation (i.e., syndiagenetic microfaults and slumps) related to detrital sedimentation (i.e., sedimentary unit A at proposed sites IG-1 and IG-2 and sedimentary unit D at proposed site IG-1); samples retrieved during the *Equanaute* dives show syn-depositional, or syn-diagenetic, deformation that could be due to tectonic instability;

4) the nature and origin of deeper reflectors; interpretation of the MCS lines implies that the deep reflectors are unconformities (or sedimentary reflectors), not thrust ramps. This question can be addressed especially at proposed site IG-2, where the deep reflectors can be alternatively interpreted as the top of a tilted (extensional) block or as a basal thrust below an eroded block.

Finally, microtectonic observations, paleostress measurements, tilting history, and paleomagnetic controls will be used together to define the tectonic regime and evolution of the transform margin. Structural results will be combined with sedimentary data (ages, nature, and depths of deposition) in order to

1) better determine the relative interplay of syn-rift and post-rift syn-transform tectonic and sedimentary processes involved in the formation of a transform margin;

2) better quantify, in time and space, the subsidence and tilting history of each main transform margin domain.

All these data are needed to define a thermo-mechanical model for transform margin creation and evolution, and for a potential comparison to models developed for oceanic fracture zones.

<u>Paleoceanographic Objectives</u>

The paleoceanographic potential of ODP Leg 159 sites stems from their proximity to the Benguela Current and West African Monsoon, from their bathymetric range (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 are 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.

Character and Origin of Atlantic Intermediate Waters

At a depth of 2100 m, proposed site IG-1 lies within intermediate and uppermost deep waters. Benthic foraminifers collected from this site should 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, D. Oppo et al., submitted) suggest that over the last several million years the character of the Atlantic's deep and intermediate waters has varied as 1) the transition between northern and southern source waters has moved north and south and as 2) their vertical distribution has reversed.

There is direct evidence that the amplitude of the north-south movement of southern source waters flowing into in 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 (D. Oppo et al., submitted) is assumed to reflect the character of intermediate waters flowing over a sill. Proposed site IG-1 should provide a more direct record of intermediate water properties, for both a longer period of time and at greater time resolution. Proposed site IG-1 should also provide a record that is upstream of southern-source intermediate waters and downstream of northern-source waters relative to the Caribbean record, helping to constrain the potential sources of intermediate waters flowing between them.

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 proposed site IG-1 and its close proximity to the West African Monsoon should offer a record of its long-term evolution and of the amplitude of its local effect on upwelling and climate.

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 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, influences 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. By using the chemistry and species compositions of benthic and planktonic foraminifers at proposed site IG-1, it may be 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.

Tropical Atlantic Biostratigraphy

The combination of relatively high sedimentation rates, stratigraphic continuity, and proximity to sources of pelagic and hemipelagic sediments at proposed site IG-1 should allow refinement and correlation of tropical marine and palynological biostratigraphies.

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

The character of waters in the deep basins of the Eastern Atlantic 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 matters from surface waters, and, on long 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). Comparison of sediments and benthic foraminifer chemistry from deep site IG-3 with shallow proposed site IG-1 and with sites previously drilled by ODP Leg 154 on the Ceara Rise in the Western Atlantic should allow the relative importance of these different influences on sediment character and water chemistry in the deep Eastern Atlantic to be determined.

Middle Miocene Stratigraphy and Climate

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 (ODP Legs 115, 130, and 154), none of these have recovered cores with both well-preserved mircofossils and a good magnetochronology. The absence of well-dated tropical-warm subtropical biostratigraphy is unfortunate, since the middle Miocene was a period of marked expansion of the Antarctic ice sheet, formation of most of the Neogene-sourced oil reservoirs of the world, and the initiation of the modern style of deep-water formation in the North Atlantic (e.g., Woodruff and Savin, 1989; Wright et al., 1992). Understanding these events is hampered by difficulties in comparing events between the tropics and the high latitudes. Proposed site IG-1 has the best opportunity to recover cores that contain well-preserved magnetic and biostratigraphic records, given its location in an area of high hemipelagic sedimentation.

Paleogene Climate History and Paleoceanography

Three principal issues could be addressed by recovery of cores by Leg 159;

1) low-latitude surface temperature history during the Paleocene and Eocene;

2) nature of the Paleocene/Eocene boundary event at low latitudes;

3) sources of deep waters during the Paleocene and Eocene.

Eocene Equatorial Sea-Surface Temperature (SST)

The early Eocene had the most equitable climate of any period of time during the Cenozoic (Dawson et al., 1976; Axelrod, 1984; Rea et al., 1990). Isotopic data suggest that both surface waters and deep waters reached their maximum temperatures in the early Eocene (Savin, 1977; Miller et al., 1987a; Stott and Kennett, 1990). High latitudes reached temperatures of 15°-17°C (Zachos et al., 1994). This warm interval lasted 3-4 m.y. and marked fundamentally different climatic conditions than were present at any other time in the Cenozoic. Latitudinal thermal gradients were probably less than 6°-8°C during the Eocene, about half the modern pole-to-equator gradient (Zachos et al., 1994).Yet the interval is poorly known both because low-latitude records are rare and those that do exist are either spot cored or disturbed by drilling through Eocene cherts. High global temperatures in the early Eocene promise a means for testing global climate models (GCM's) run under conditions of increased atmospheric CO_2. Knowledge of low-latitude temperatures provides a major constraint on GCM's, since equatorial seas play a major role in regulating heat exchange with the atmosphere. It is possible that the relatively equitable climates of the Eocene were promoted by higher heat transport between latitudes. Hence, low-latitude temperature data are needed to constrain model runs of Paleocene climate. More generally, the Eocene warm interval provides a test for climate models that integrate latitudinal thermal gradients, atmospheric CO_2 levels, and ocean-atmosphere heat transports.

The Paleocene/Eocene Boundary Event

The early Eocene warm interval followed an abrupt extinction of benthic foraminifers and a marked excursion in the isotopic chemistry of both benthic and planktonic foraminifera (Miller et al., 1987b; Rea et al., 1990; Kennett and Stott, 1991). There is good evidence that production of Antarctic Deep Water may have been shut down in at least two or more short (100-200 k.y.) events, which allowed bottom waters formed at low latitudes to fill the deep ocean (Kennett and Stott, 1991). Well-preserved foraminiferal assemblages at proposed site IG-1 should provide a detailed record of the duration, number, and history of the Paleocene-Eocene transition. Recovery of the Paleocene-Eocene sequence at the deeper sites (proposed sites IG-2 and IG-3) would provide a depth transect that could be used to evaluate the vertical structure of deep and intermediate waters.

Paleocene and Cretaceous Deep-water Formation

Stable-isotope evidence suggests that the Paleocene-Eocene event was a brief exception to the general formation of deep waters adjacent to Antarctica (Miller eta l., 1987a, 1987b; Barerra and Huber, 1990, 1991; Pak and Miller, 1992). The Southern Ocean has consistently had some of the youngest waters found in the deep sea since at least the Late Cretaceous (Barerra and Huber, 1990). However, the stable-isotope data are strongly biased toward studies of high southern-latitude cores and cannot eliminate the possibility that there may have been other sources of deep or intermediate water. Indeed, marked reductions in the $\delta^{13}C$ latitudinal gradient during the Paleocene suggest that there may have been either very low rates of surface-water production or other sources of deep water. Norris and Corfield (submitted) have found that the North Atlantic was filled with young, warm waters during the early Paleocene and Cretaceous. Drilling during Leg 159 could provide equatorial sites to monitor the possible contribution of deep waters from the low latitudes and the mixing of these waters with Southern source waters.

We have little information about deep waters for the Early and middle Cretaceous. However, the depth transect from proposed sites IG-1 to IG-3 offers the possibility of reconstructing the structure of deep waters when the North Atlantic was a relatively enclosed basin.

The Cretaceous-Paleocene Event

Leg 159 offers the opportunity to recover a complete Cretaceous/Paleogene (K/P) boundary along a depth transect that could be used to describe the climatic and biotic events prior to the extinction as well as the sedimentological, geochemical, and biotic effects of the proposed bolide impact. The location of the Leg 159 drill sites in an area of hemipelagic sedimentation suggests that the K/P boundary sequence, if present, should be unusually expanded and contain well-preserved calcareous microfossils. Although many "complete" boundary sections exist, nearly all deep-sea records are very thin, disturbed by bioturbation or drilling, or contain poorly preserved microfossils. Even a single high-resolution record across the boundary would be valuable to

1) recover an expanded record of the latest Maastrichtian to infer whether there were major changes in low-latitude climate and pelagic biota prior to the K/P boundary; results from Southern Ocean and Indian Ocean sites suggest that SST decreased throughout the late Maastrichtian and reached temperatures cool enough to allow formation of permanent glaciers on Antarctica; presently, the best low-latitude K/P boundary sequences are from shallow-marine settings that may not be representative of pelagic conditions;

2) evaluate the recovery of the oceans and biotas following the extinction; some of the most well-preserved Paleocene/Cretaceous calcareous microfossil records come from shelf and hemipelagic sections; sections could provide evidence for the magnitude of the extinctions, their duration, and patterns of diversification following the event; cores containing records of the earliest Paleocene should also be suitable for studies of the geochemical history of the oceans in the absence of a diverse plankton community.

Recovery of Mid-Cretaceous Anoxic Sediments

Drilling at proposed site IG-1 has the potential to penetrate laminated, organic-rich sediments deposited from anoxic bottom waters. The location of the site, in the Central Atlantic, affords the opportunity to examine the temporal evolution of bottom-water oxygen conditions as tectonism transformed 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 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), while 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 anticipate that recovery of anoxic middle Cretaceous sediments will 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 most 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 middle Cretaceous black shales to reconstruct the Os isotopic composition of 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 an 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 our findings will show that local restricted basins maintained distinct Os isotope signatures until rifting and concomitant ventilation shifted Os isotope ratios to open-ocean values.

An associated avenue of investigation is the pore-water geochemistry of anoxic sediments. If Cretaceous anoxic sediments yield sufficient pore-water Mo, U, and V elements with similar geochemical affinities to Re and Os, the scale of the diagenetic mobility in this sedimentary environment can be investigated. Less well-lithified sediments from the later portion of the Cenozoic record may also be subject to similar analyses if high productivity associated with the West African Monsoon has resulted in deposition of organic-rich anoxic sediments. It is more likely that poorly lithified sediments would yield adequate amounts of pore water. Re-Os studies analogous to those described above will also be undertaken if organic-rich Cenozoic sediments are recovered.

Opening of the Cretaceous Atlantic Gateway

Based on the sedimentary record, proposed site IG-1 results should better constrain history and conditions of the connection between the Central and South Atlantic through the Equatorial Atlantic. The drilling results should particularly help to determine

1) the age of the gateway (potentially as far back as the Aptian-Albian);

2) the nature of the gateway (an Atlantic gateway vs. a gateway crossing Africa through the Sahara and the Benue Basin);

3) the bathymetric evolution of the area.

The same site will help determine the middle (from Aptian-Albian) and Late Cretaceous paleoenvironmental evolution, constraining

1) the age and nature of the first marine sedimentation;

2) the evolution of paleoenvironments (bathymetry, salinity, oxygenation, surface and bottom circulation, upwellings) and biofacies (Atlantic or African gateway) during the middle and Late Cretaceous;

3) the initiation of an open-marine environment and communication with the open ocean (possibly from the Albian);

4) the initiation of cold-water deep currents originating from the South ("paleo-Benguela Current") and influence on the productivity and dissolution of carbonates;

5) the probable sampling of the well-known anoxic event (black shales) at the Cenomanian/ Turonian boundary, as a regional event or a global event;

6) the origin of sedimentary onlaps and toplaps along the northern CIG Marginal Ridge slope; are they due to tectonic or isostatic events (uplift or subsidence of the marginal ridge), or to environmental variations (sedimentation rate, currents, sea level) in proximal fans (sediments derived from the south, i.e., from the marginal ridge) or distal fans (detrital sediments from the north, i.e., the African coasts)?

7) the record of Cenozoic global events in an area influenced by deep-water circulation along the Romanche Fracture Zone.

Potential Lithospheric Implications

Available MCS and refraction data suggest that the oceanic crust emplaced at this ridge/transform intersection was created at a very low magmatic-accretion rate by intrusion of discontinuous, differentiated magmatic bodies within partially serpentinized peridotites (Sage, 1994). These mechanisms and the serpentinization should have been controlled by faulting.

Unfortunately, the thickness of the sediments precludes reaching the oceanic crust in this area. However, we expect to obtain information on the oceanic crust at proposed site IG-3, located near the continent/ocean boundary, including the nature of the minor ridges, involvement of magmatic rocks near the transform fault, and investigation of hydrothermal activity.

DRILLING PLANS AND STRATEGY

Selection of the Leg 159 drill sites was based on a detailed set of single-channel and multichannel seismic reflection profiles (Fig. 3) and was constrained by the thickness of the sedimentary cover within the Ivorian Basin, on the marginal ridge, and in the adjacent oceanic abyssal plain (Figs. 7, 8, and 9) and by the need to develop a drilling program that can be completed during a single ODP leg.

Two sites are located on the marginal ridge (proposed sites IG-1 and IG-2; Figs. 3, 12, 13, 15, and 16) in areas where deep targets can be achieved because of a relatively thin sedimentary cover (1600 and 780 m, respectively). In addition, a third site is located on a minor ridge, near the transition between the oceanic fracture zone and the continental transform margin (proposed site IG-3; Figs. 3, 7, and 14).

These three sites constitute an east-west, along-strike transect which will permit a study of the lateral evolution of the transform margin from a thick continental crust to a very thinned crust. Because proposed site IG-3 is closer to the continent/ocean boundary, comparison with proposed sites IG-1 and IG-2 will also serve to illustrate the expected changes in tectonics when moving across the continent/ocean boundary toward the oceanic crust.

In addition to the primary sites, a number of alternate sites have been proposed. Proposed site IG-1bis serves as a reserve to proposed site IG-1 in case this site proves undrillable or has to be terminated due to safety (hydrocarbon) considerations. It is located higher on the marginal ridge, where the Cenozoic sedimentary cover is considerably reduced, therefore allowing easy access to the older deposits on the ridge, which are considered crucial for the structural history. The reduced sediment cover makes this site less informative for the paleoceanographic and subsidence analysis of the ridge. Should proposed site IG-1 have to be terminated at a shallow depth, proposed site IG-1bis will permit the deeper objectives to be met safely and without the need for time-consuming drilling of a thick sediment cover. Additional alternate sites (IG-2B, IG-2C, and IG-3bis) are close to each of the three primary sites.

The proposed plan presently calls for drilling to commence with a program of triple advanced piston core (APC) recoveries from the top 200 mbsf at proposed site IG-1. The last of these holes will then be deepened, using the extended core barrel (XCB) to 300 mbsf before being replaced by the standard rotary core barrel (RCB). Using the RCB, a new hole will be started, with coring proposed to 800 mbsf, after initially washing through the upper 300 m. This hole will be logged, and then a final hole started by jetting in a reentry cone together with a casing string to stabilize the top of the hole for the final deep penetration. Casing is planned to be set to approximately 520 mbsf, although the exact length will be determined by actual hole conditions. After casing has been set and the drill washed to 800 mbsf, coring will recommence to 1600 mbsf; then, three suites of logs will be run (Quad-combo, geochemical, and formation microscanner or FMS). At proposed site IG-1, temperature measurements will be made by the water sampler temperature probe (WSTP) at least every 100 m within the APC-cored part of the hole. A temperature-logging run will extend coverage to the lower parts of the hole. The ADARA temperature tool may be used to gain extra temperature measurements. These measurements are considered important at this site. If at any time proposed site IG-1 is terminated due to safety or other operational difficulties, the deep targets of the marginal ridge will be achieved by drilling proposed site IG-1bis. As the sediment cover there is less, the older deposits on the marginal ridge might be readily recovered. Depending on how deep the drilling at proposed site IG-1 progresses prior to termination, it may be possible to wash ahead to the deeper stratigraphic beds before coring is resumed at this site.

The second primary site to be drilled is proposed site IG-3. Operations will commence with RCB coring from the mud line. At this site, the target is the acoustic basement imaged on seismic lines, the character of which is unknown. Drilling will attempt to reach this target and penetrate 150 m into the acoustic basement to an estimated total depth of 850 mbsf. Drilling will be terminated at 850 mbsf or higher in the basement if bit failure occurs. A standard three-log program will be undertaken throughout the length of the cored section. If time permits, as a result of time saved at proposed site IG-1, the top 200 m of the sedimentary column may be sampled by triple APC coring at the start of the drilling operation.

The final primary drill site is proposed site IG-2. RCB coring is scheduled from the mud line to a depth of 780 mbsf. No change of drill bit is anticipated to reach the primary target, a structurally complicated section at the base of the proposed hole. A standard three-run logging suite is planned for this hole. If time remains at the end of the program, the top 200 m of sediment will be cored an additional two times by APC to improve the paleoceanographic coverage.

Sampling Strategy

In addition to the primary tectonic and paleoceanographic objectives of the cruise, there may be a need to take samples for physical-property studies, such as triaxial tests for seismic anisotropy. Where possible, these samples will be taken from the third hole cored by APC in those sections. In other instances, the location and number of any such samples will be governed by the nature of the lithology, the amount and quality of recovery, and consideration of alternative requests for the material. To ensure successful completion of the paleoceanographic objectives, triple APC cores will be taken at proposed site IG-1, and, if time permits, at proposed sites IG-2 and IG-3. We expect that normal sampling density may be exceeded over certain sections to ensure the high resolution required to answer the specific paleoceanographic questions.

Logging Strategy

The standard three-tool strings (quad-combo, geochemical, and FMS) have been selected for use in Leg 159 holes drilled deeper than 400 mbsf. In holes shallower than 400 mbsf, logging will occur where it assists in meeting the scientific objectives of the site. The tools are described briefly below and are described in greater detail in the Lamont-Doherty Earth Observatory Logging Manual.

The suggested logging plan will provide important information on

1) lithological characterization via standard geochemical and geophysical log;

2) identification of seismic reflectors using synthetic seismic profiles generated from velocity and density logs;

3) present orientation, frequency of occurrence, and possibly nature of infill of brittle deformational features, and foliation/bedding orientations, using the FMS.

Quad-combo Tool String

This will be the first logging tool string to be run in the hole, measuring formation velocity, resistivity, density, and natural gamma-ray activity in a single logging pass. Sonic velocity data are combined with density measurements to calculate an impedance log and generate synthetic seismograms. These wavelet logs are used to tie the seismic information directly to the logs and core data. The density and resistivity logs are valuable for providing lithologic information on the borehole wall. This tool string also provides continuous physical-property measurements of density and porosity at half-foot (0.1524-m) intervals or, alternatively, at 1-inch (0.025-m) and 2-inch (0.05-m) measurements of density and porosity respectively when logged in the "high resolution" logging mode.

Geochemical Tool String

During the cruise, the geochemical tool string measures relative concentrations of Si, Ca, Fe, S, H, and Cl and wet weight percentages of K, U, Th, and Al. Shore-based processing produces dry weight percentages of these major rock-forming elements and of Gd and Ti. These elemental logs can be used to infer lithologic information from the hole. Matrix inversion programs are available at the shore-based lo-analysis centers. From these inversion programs, calculations can be done with these data. Chemical measurements with this tool are taken every 0.1524 m over the logged interval.

FMS

The FMS provides oriented, two-dimensional, high-resolution images of the variations in microresistivity around the borehole wall. The string also includes a general-purpose inclinometer tool (GPIT), which measures the declination and inclination components of the Earth's magnetic field vector and allows for the orientation of the microresistivity measurements. The FMS can be used for correlation of coring and logging depth, orientation of cores and location of the cored sections when recovery is less than 100%, mapping of sedimentary structures and interpretation of depositional environments, as well as providing very high-resolution resistivity measurements (3 mm), which can be transformed into high-resolution porosity and density measurements.

Temperature Tool

The BRG temperature tool is recommended for usage with the Quad-combo and geochemical strings at proposed sites IG-1 and IG-3. Temperature logging is important to identify zones of active fluid flow in this transform margin.

BHTV

If time permits, the BHTV may be used for a correlated study with the FMS, due to the high priority of the structural information on this leg.

Sidewall Entry Sub (SES)

Due to the nature of the anticipated lithologies, calculated logging times include the use of the SES. The decision on whether or not to use this tool will be made on board, based on the consolidation of the sediments, the possibility of swelling clays, the occurrence of hard ledges, and general weather conditions. The use of this tool adds an additional 10 to 15 hr of logging time, but significantly reduces the risk of not obtaining logs or of losing the tools.

PROPOSED SITES

Proposed site IG-1 (Fig. 12) is dedicated to a study of the northern CIG Marginal Ridge slope and of its undeformed sedimentary cover. Complementing the deepest sediments retrieved during the *Equanaute* submersible dives, this site will document the entire sedimentary column covering the transform margin, including 1) units coeval with the nearby Ivorian rifting, 2) units subsequent to rifting (but coeval with transform faulting), 3) units posterior to transform faulting (but contemporaneous with thermal uplift), and finally 4) the sedimentary units covering the passive margin after the end of transform faulting.

Information obtained from this site will also constrain 1) the formation and subsidence of the fossil marginal transform ridge; 2) the style, intensity, and timing of strike-slip deformations; 3) the timing of potential block rotations; and 4) the age and nature of the first marine sediments related to the opening of the Equatorial Atlantic gateway.

Proposed site IG-2 (Fig. 13) is dedicated to a study of the western extremity of the CIG Marginal Ridge. In this area, the undeformed sedimentary cover is thin but incomplete (sedimentary units B, C, and E are missing). However, the available post-rift cover will allow comparison between the subsidence of the two marginal-ridge sectors, proposed site IG-1 (on the eastern continental side) vs. proposed site IG-2 (on the western extremity near oceanic crust).

The main goal of proposed IG-2 site is to drill the top of a tilted block that may have undergone extension, strike-slip movements, and potential structural inversion. Information on the style, intensity, and timing of deformation is necessary to understand the creation of this part of the marginal ridge.

Paleomagnetic studies within the syn-transform sediments will be used to investigate possible block rotations.

Finally, study of the diagenesis, and possible metamorphism, of the syn-transform sediments will be used to constrain the P-T field, associated with both transform shearing and post-transform heating due to the proximity of adjacent oceanic crust.

Proposed site IG-3 (Fig. 14) is dedicated to the study of one of the en échelon minor ridges that characterize the westernmost transform margin, near its junction with the fossil Romanche Fracture Zone. In this area, the lower margin has possibly experienced two transform-related events, transform motion within an intracontinental transform fault and transform motion within a continent-ocean transform fault.

The nature (deformed sediments, continental basement, oceanic basement?) of these minor ridges is the main target of drilling at this site. The type of deformation that has generated the en échelon pattern would also be determined from microstructural analysis.

Structural observations will be used to establish the two potential successive transform events (intracontinental and continent-ocean). Finally, hydrothermal activity and/or heating processes of the minor ridge sediments and/or basement are expected, due to the proximity of oceanic lithosphere.

Alternate proposed site IG-1bis (Fig. 15) is located on the northern slope of the marginal ridge south of proposed site IG-1. This site would address the same major topics but cannot document the entire sedimentary column, since seismic units pinch out against the A2 and A1 units. However, proposed site IG-1bis may allow us to penetrate deeper into basal ridge units. The site, based on a 1000 m penetration, may become a reentry hole in order to document the deeper sequences, A1-A2.

Proposed sites IG-2B and IG-2C (Fig. 16) are alternates for proposed site IG-2. The main objectives are to document the style, intensity, and timing of deformation of this part of the marginal ridge close to the ocean/continent boundary. The planned penetration at these sites is about 800 m and will document mostly the A1 and A2 units. The undeformed sedimentary cover is incomplete and about 300 m thick.

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TABLE 1 - Time Estimates for Leg 159 Primary Sites

Proposed Site	Latitude	Longitude	Seismic Line	Shotpoint	Water Depth (m)	Penetration (m)	Drilling Time (days)	Logging Time (days)	Time on Site (days)	Transit Time (days)
										From Dakar
IG-1	03°37.70'N	02°44.10'W	MT 02	1690	2100	1600	21.5	3.8	25.3	5
IG-2	03°26.60'N	03°03.50'W	MT 05	2010	3315	780/800	6.7 or 9.4*	2	8.7 or 11.4*	0.2
IG-3	03°15.15'N	03°10.95'W	MT 01	2190	4630	750/800	8.7 or 12.2*	2	10.7 or 14.2*	6.8
										To Las Palmas
SUBTOTAL:						3200	36.9	7.8	44.7	12

GRAND TOTAL: 56.7 days at sea

* - Holes will be tripled APC if time is available

TABLE 2 - Time Estimates for Leg 159 Alternate Sites

Proposed Site	Latitude	Longitude	Seismic Line	Shotpoint	Water Depth (m)	Penetration (m)	Drilling Time (days)	Logging Time (days)	Total Time (days)
IG-1bis	03°35.00'N	02°44.00'W	MT 02	1580	2085	1000	6.5	1.8	8.3
IG-2B	03°26.10'N	03°04.50'W	MT 05	2050	3530	500	7.3	1.8	9.1
IG-2C	03°27.60'N	03°01.00'W	MT 05	1900	3205	500	7.3	1.8	9.08
IG-3bis	03°14.85'N	03°10.80'W	MT 01	2200	4725	800	7.9	1.9	9.8

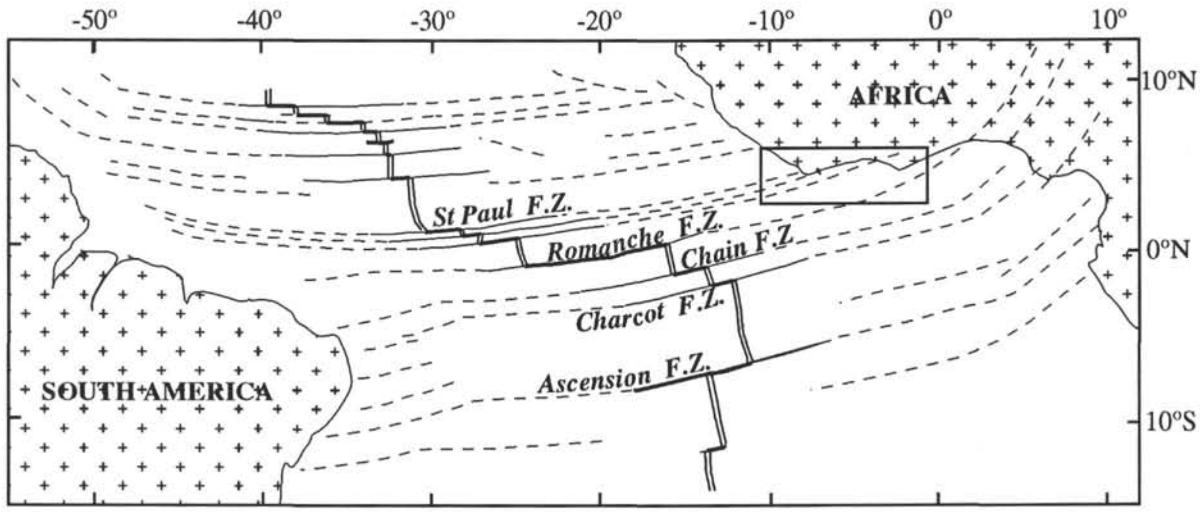


Figure 1a. Fracture zones in the Equatorial Atlantic and associated continental margins.

Figure 1b. Geodynamic sketch of the CIG Margin and the different ocean-continent transitions. Shaded area: oceanic fracture zones and marginal ridges.

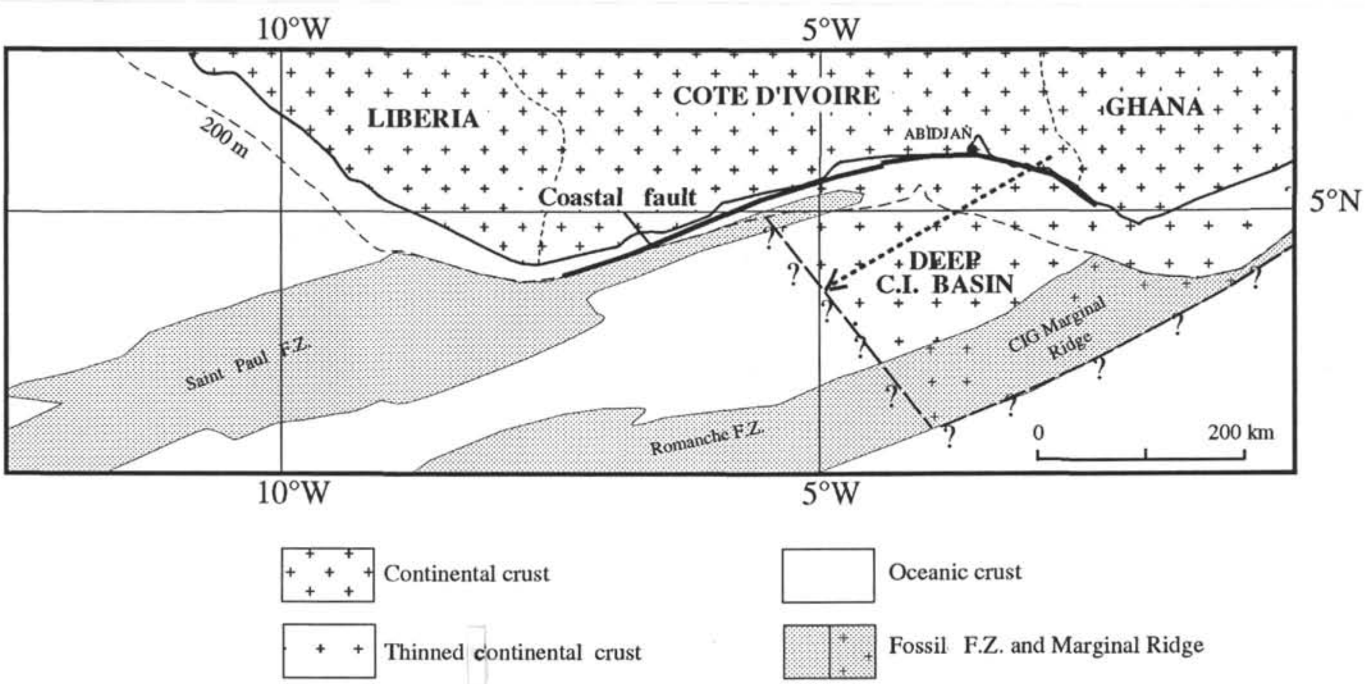


Figure 1. Geodynamic, geological, and bathymetric framework of the CIG Transform Margin.

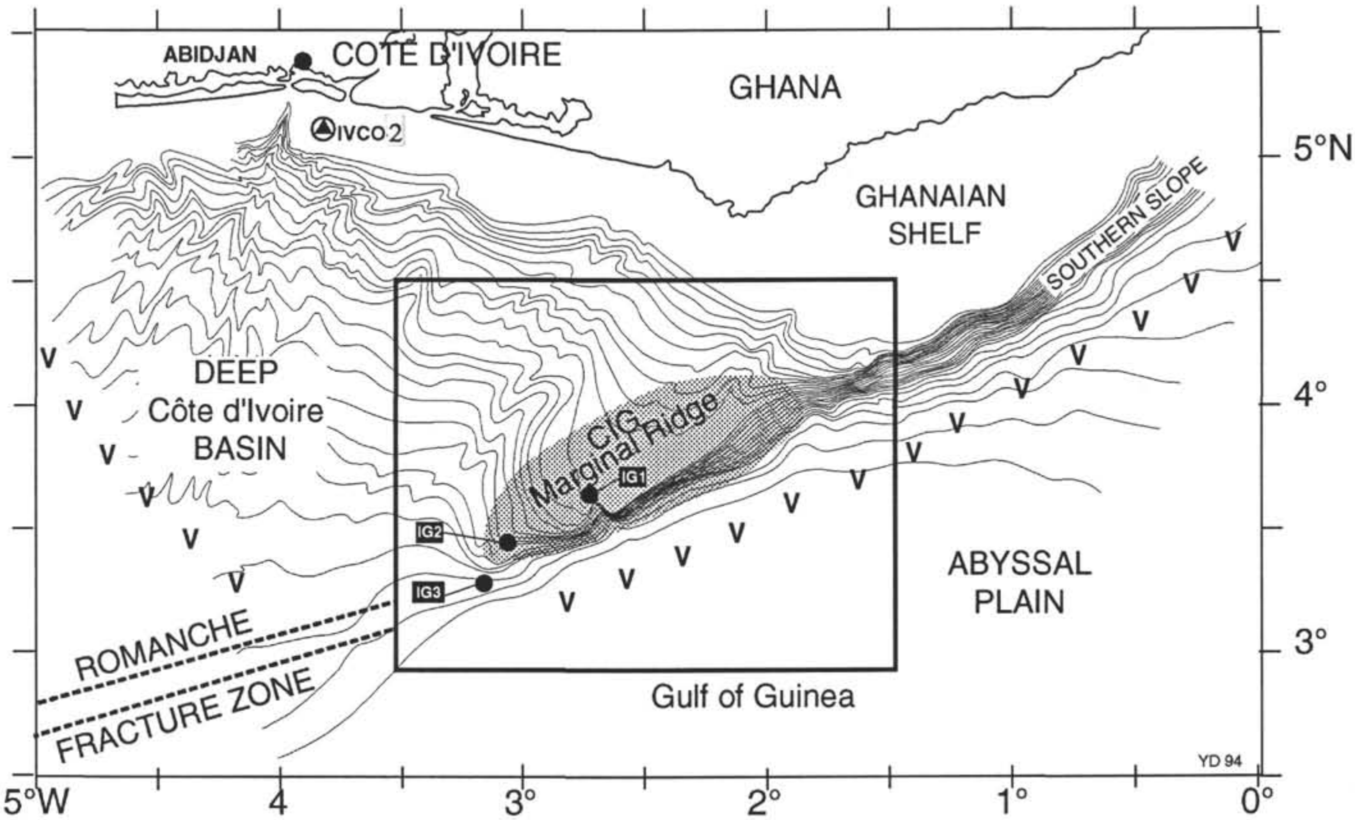


Figure 1c. Simplified bathymetry and main morphostructural domains of the CIG Transform Margin. The solid circles show locations of proposed ODP Leg 159 sites, and the triangle, the location of hole IVCO2. The V indicates oceanic crust, older west of the Ivorian Basin than southward in the Gulf of Guinea. A simplified structural sketch map of the area within the box is illustrated in Fig. 7.

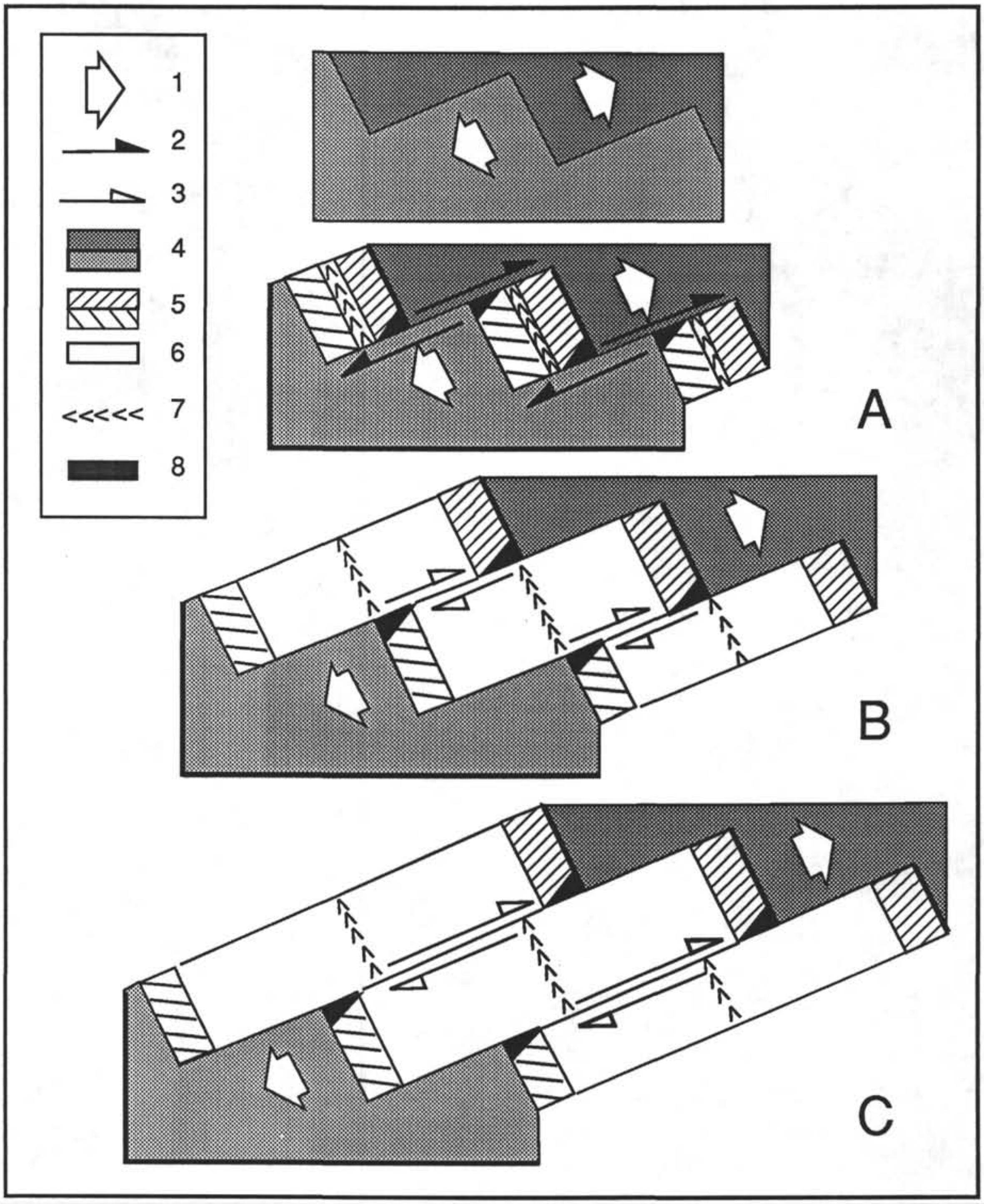


Figure 2. Plan view and 3-dimensional sketch depicting the evolution of a transform margin.

Figure 2a: Main stages of a rift transform margin:

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

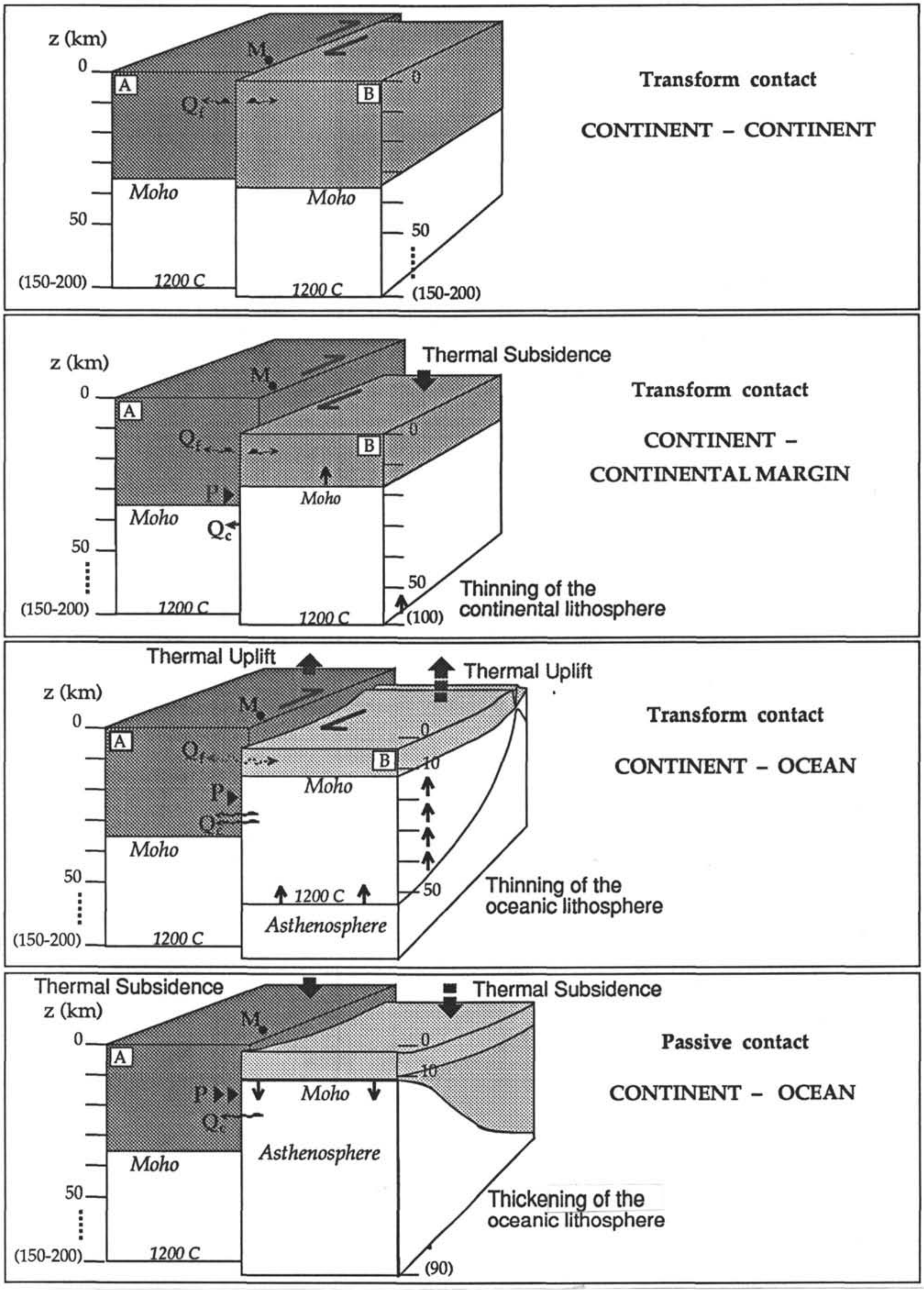


Figure 2b. 3-dimensional sketch of the evolution between two plates moving in a transform contact. Qf - friction heating. Qc - thermal exchange. P - pressure gradient. M - reference point on continental plate.

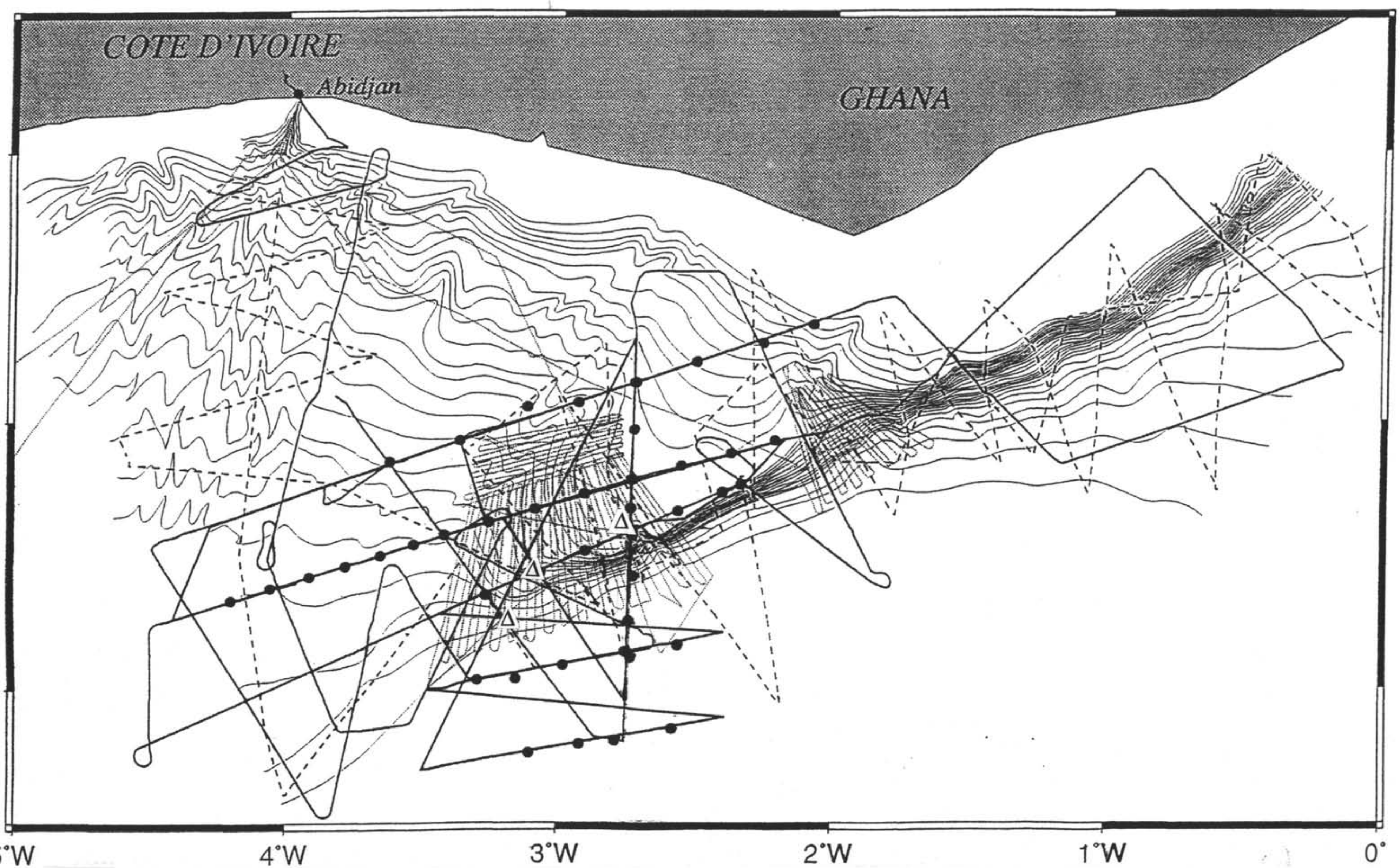


Figure 3. Recent geophysical data collected on the CIG Transform Margin shown on a simplified bathymetric map of the margin.

Triangles - first priority sites of ODP Leg 159
Dashed lines - single channel seismic lines (*Equamarge*, 1983)
Thin dotted lines - single channel seismic lines and swath bathymetry (*Equamarge*, 1988)
Solid lines - multichannel seismic reflection lines (*Equasis*, 1990)
Solid circles - location of OBS deployments (*Equaref*, 1990).

The *Equanaute* dives were performed along the southern slope of the CIG Marginal Ridge in the two areas surveyed by swath bathymetry.

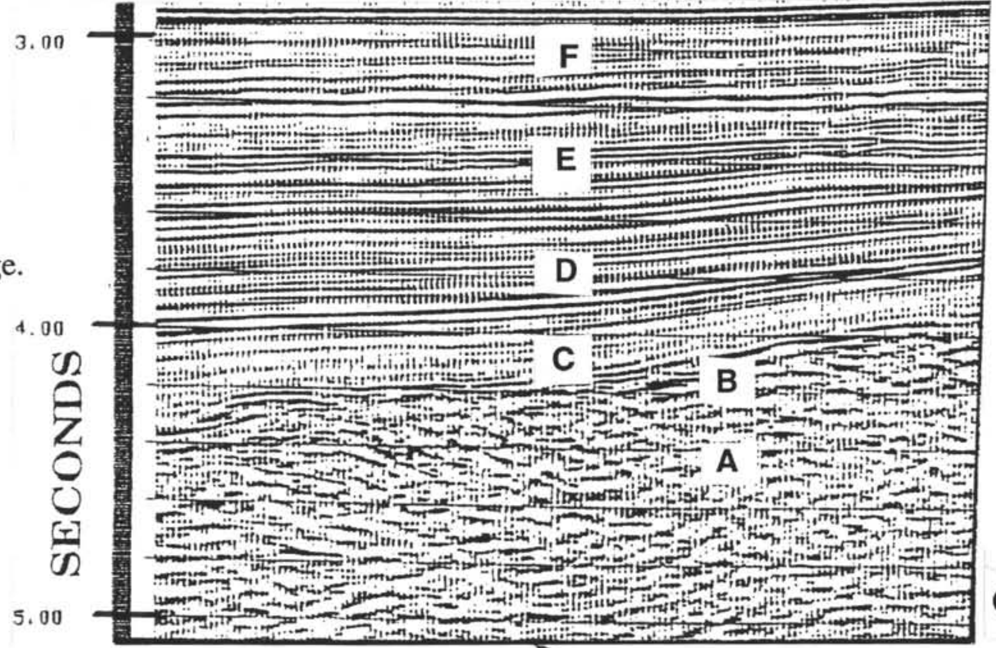


Figure 4. The main sedimentary units and probable correlations in the Ivorian Basin and Marginal Ridge.

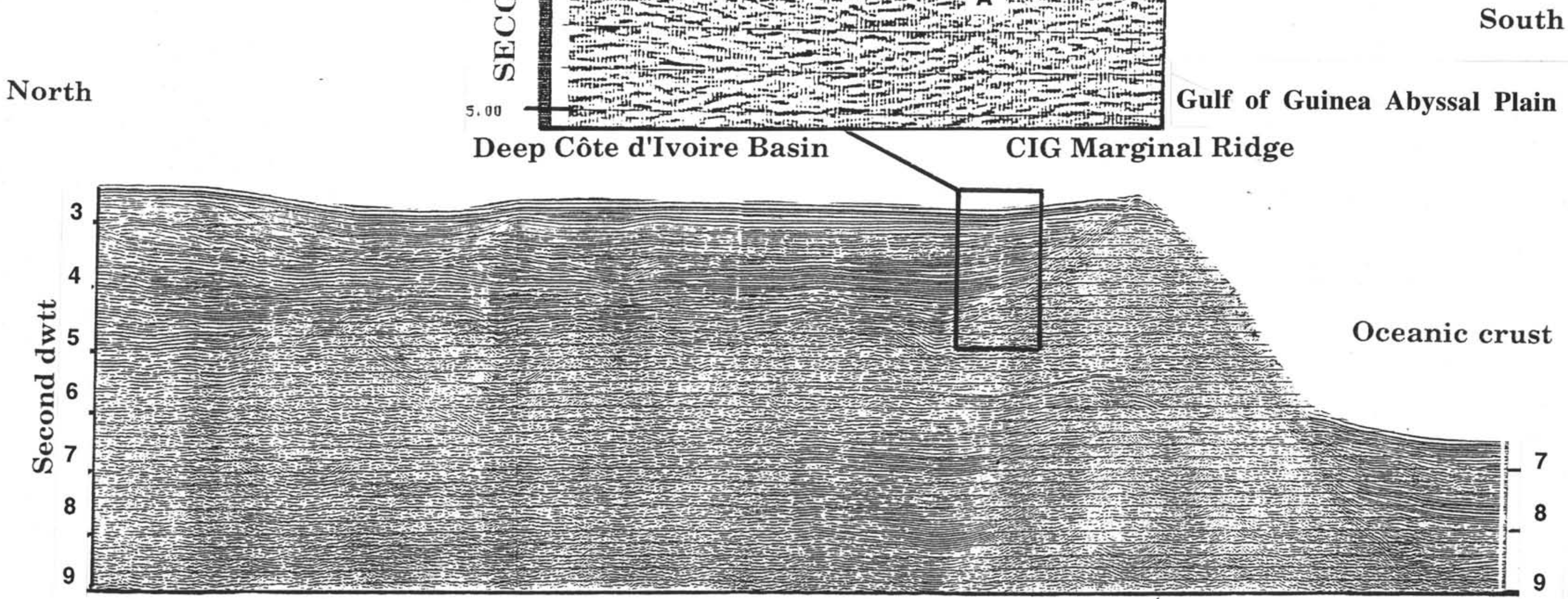


Figure 5. A typical MCS profile across the deep Ivorian Basin and the Marginal Ridge (to the south). Line MT02 (location on Fig. 3).

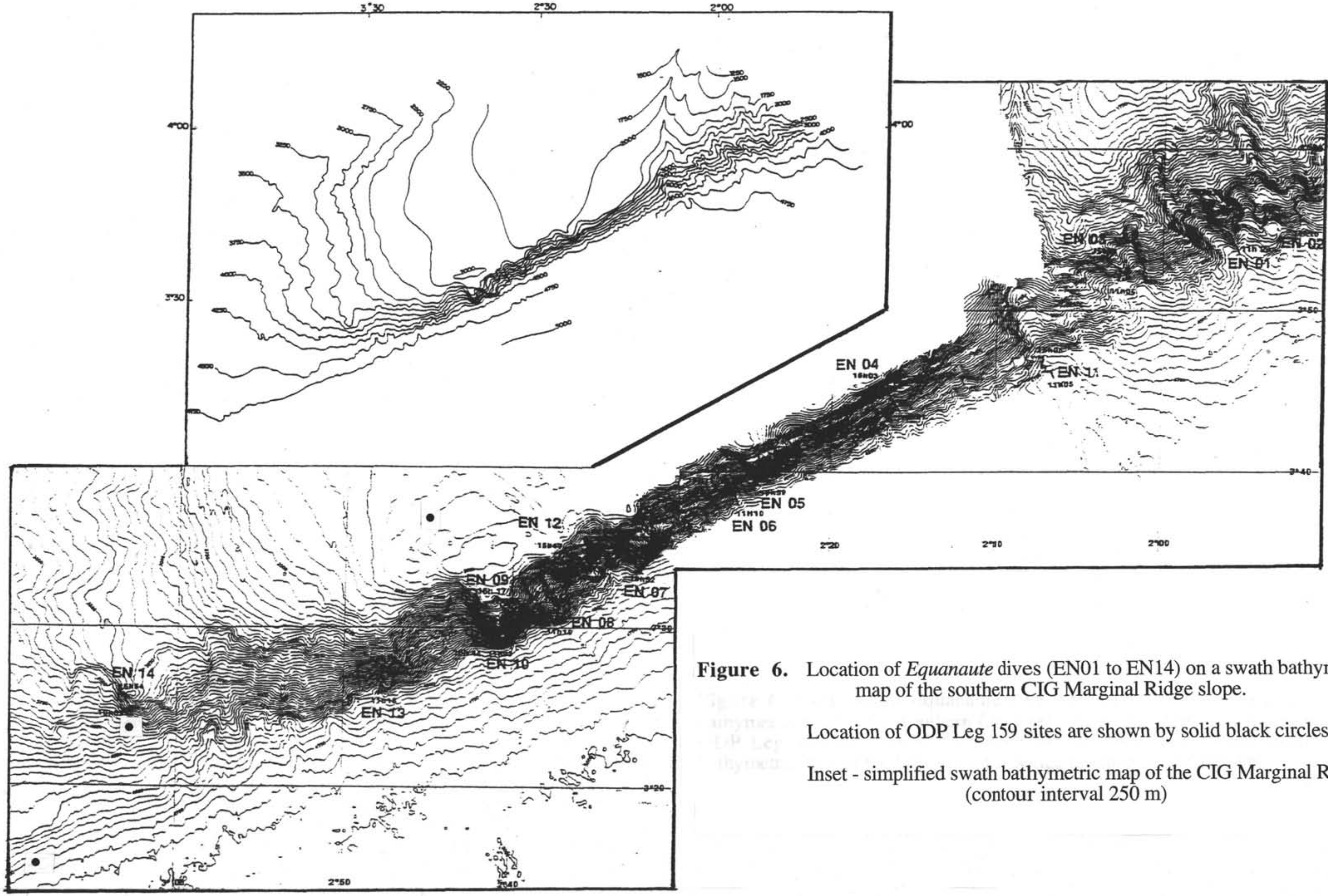


Figure 6. Location of *Equanaute* dives (EN01 to EN14) on a swath bathymetric map of the southern CIG Marginal Ridge slope.

Location of ODP Leg 159 sites are shown by solid black circles.

Inset - simplified swath bathymetric map of the CIG Marginal Ridge (contour interval 250 m)

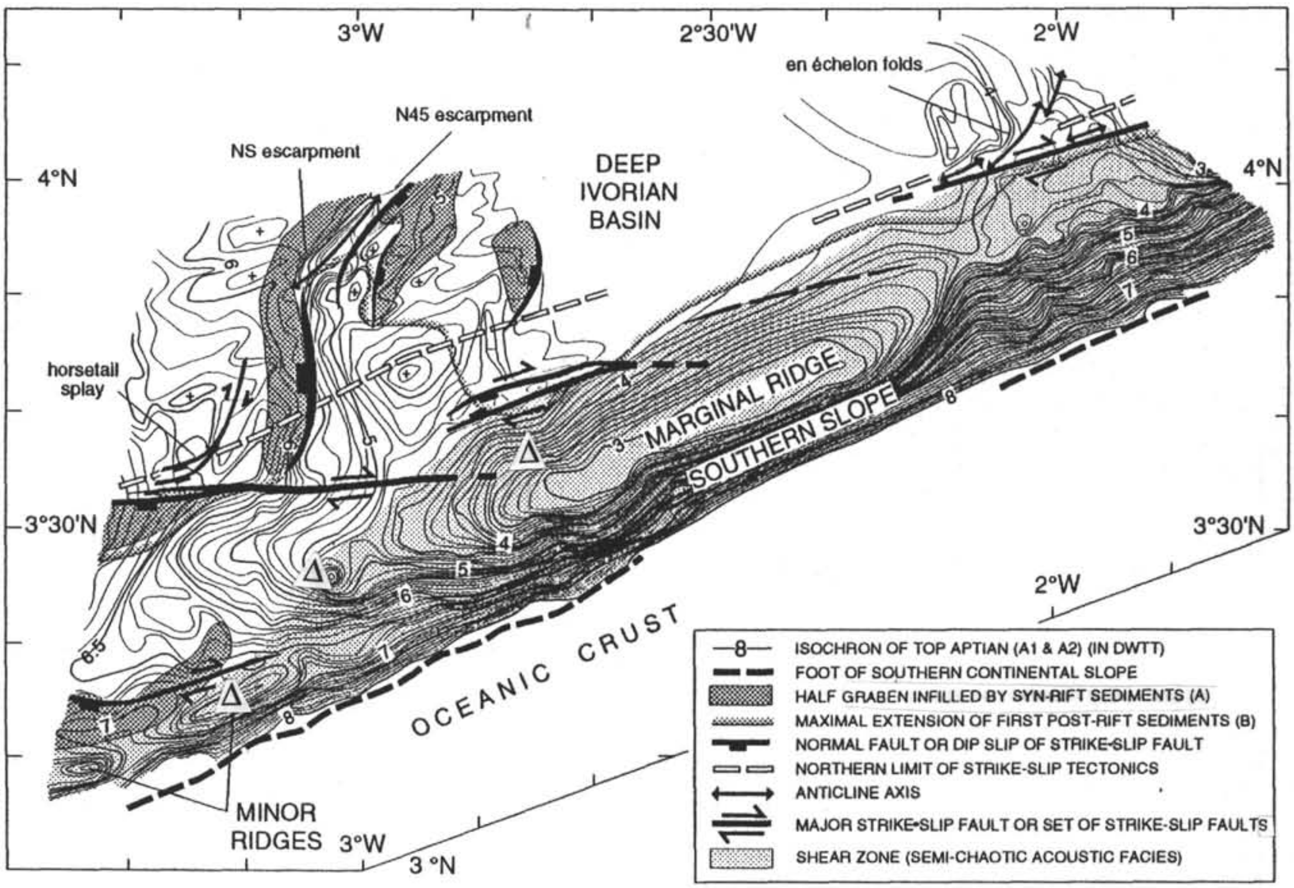


Figure 7. Simplified structural sketch of the CIG Marginal Ridge and surrounding area. Depth is shown in two-way travel time to the top of syn-rift unit A. Triangles mark the locations of ODP Leg 159 first-priority sites.

Figure 8a. Line MT03 across the eastern segment of the CIG Ridge showing the main acoustic units and their relationships.

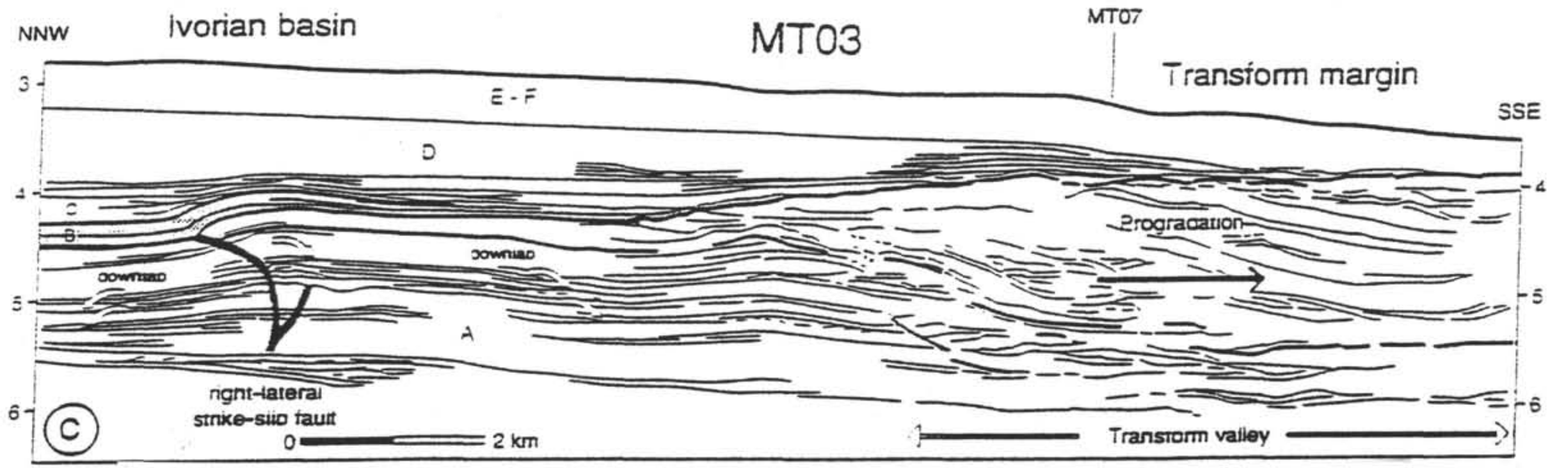


Figure 8b. Line MT02 (also shown on Fig. 5) across the deep Ivorian Basin and the Marginal Ridge (central segment).

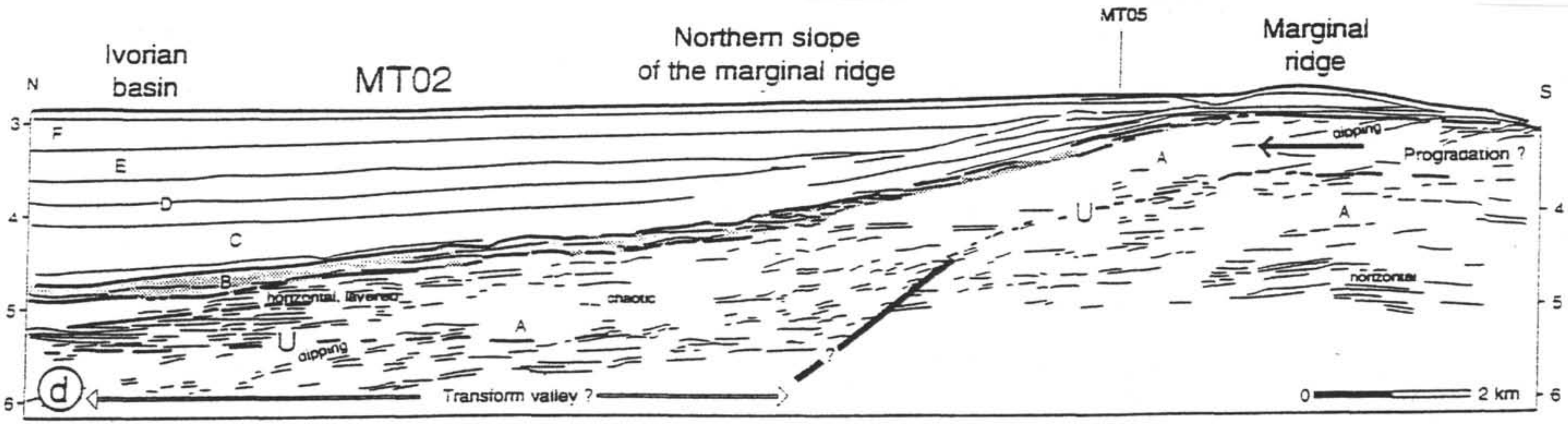


Figure 8. Tracing of MCS lines MT03 and MT02 (location on Fig. 3).

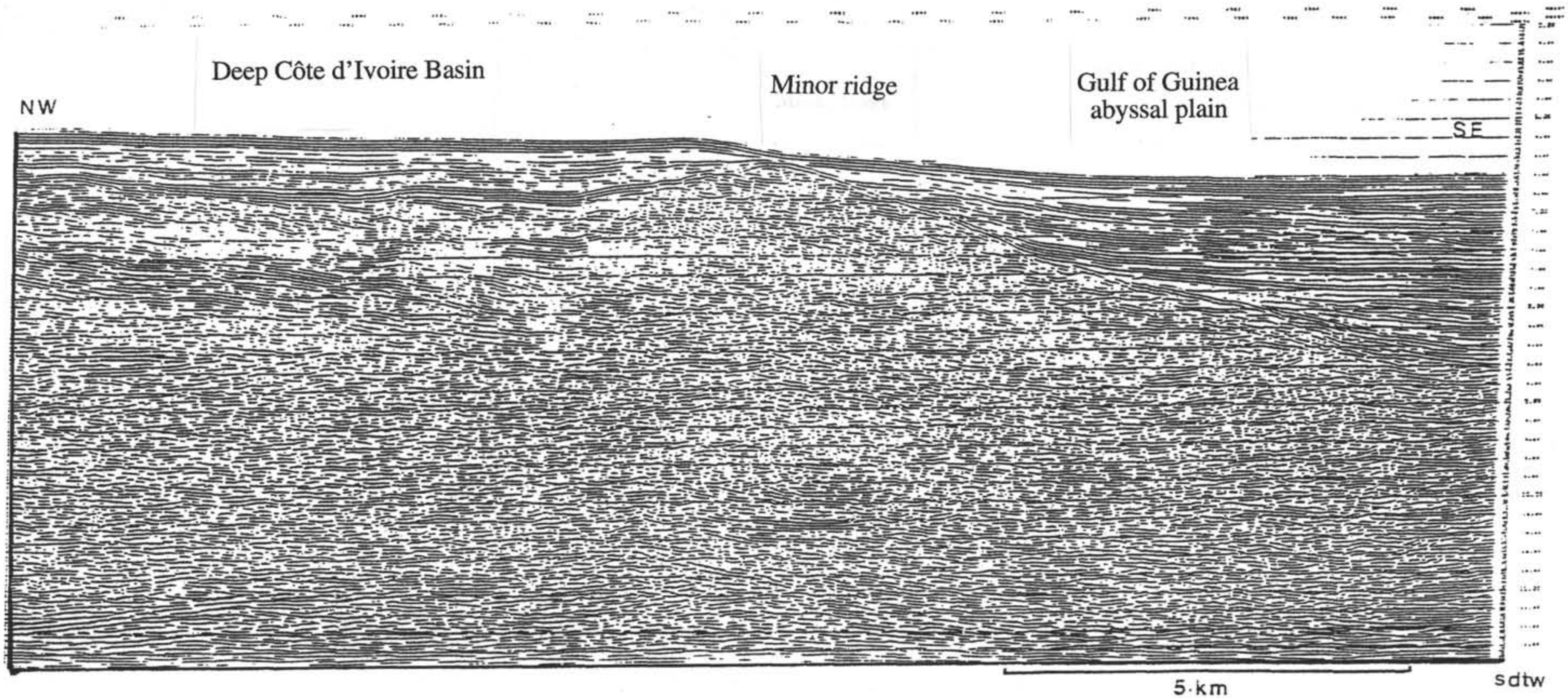


Figure 9. MCS line MT01 (location in Fig. 3) showing one of the minor ridges at the base of the southwestern CIG Marginal Ridge slope toward its transition with the fossil Romanche Fracture Zone.

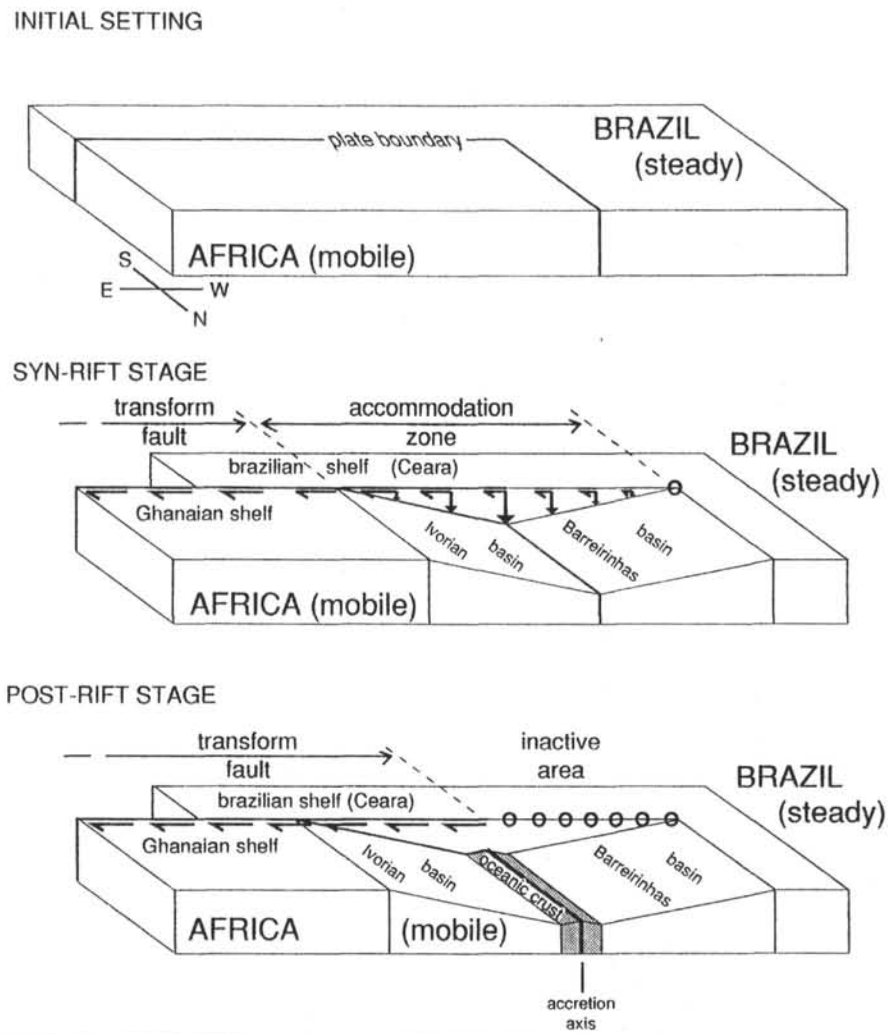


Figure 10. Kinematic evolution of the CIG Transform Margin and divergent deep Côte d'Ivoire Basin (view from the north). Brazil is supposed to be fixed. Arrows indicate horizontal and vertical relative motions (strike-slip and dip-slip faults, respectively) between the steady plate and the moving plate.

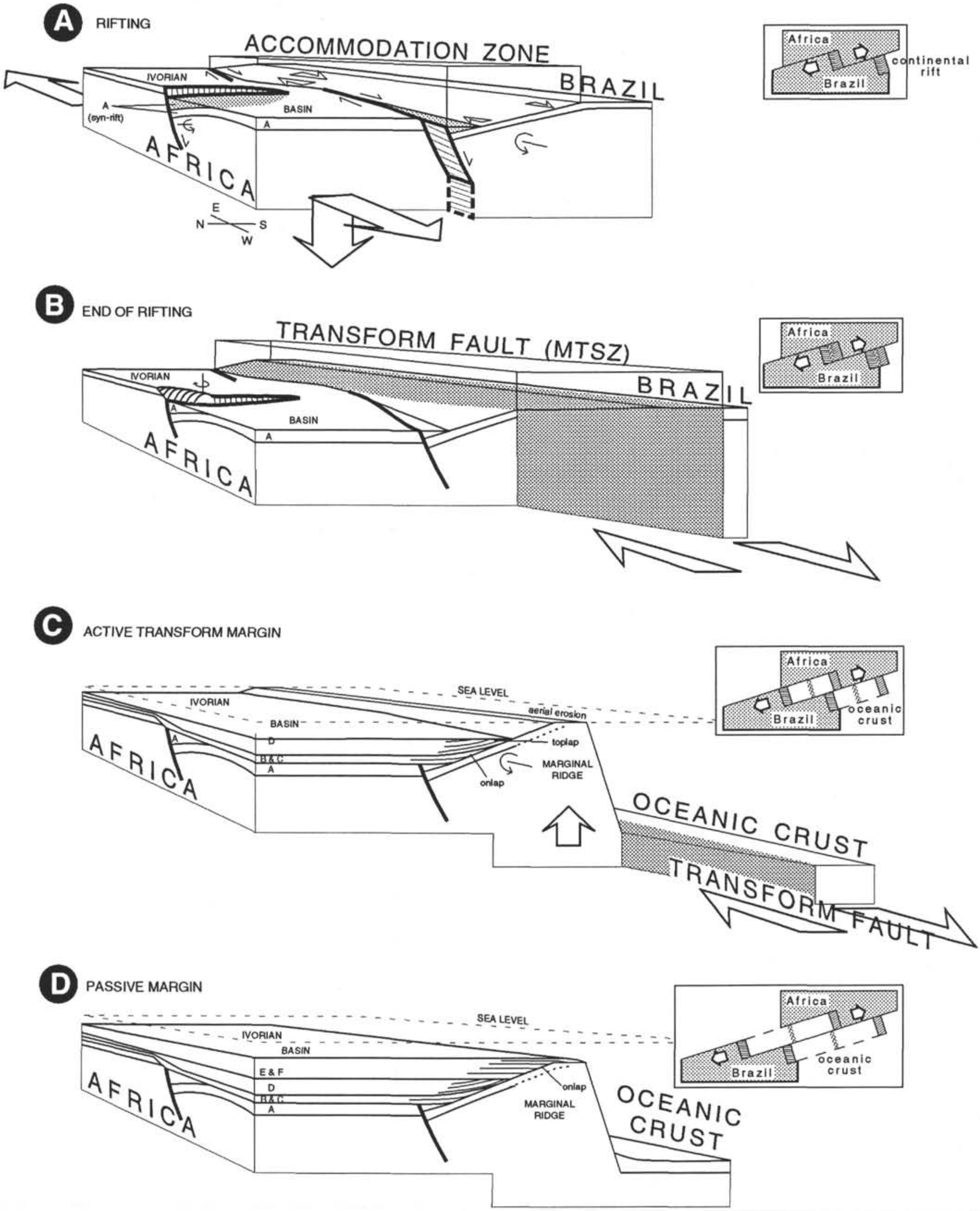


Figure 11. Four main stages in the evolution of the CIG Margin (view from the west-northwest).

Stage A - stippled areas show syn-rift basins (divergent basins and marginal ridge)
Stages B and C - shaded belt indicates main transform domain

PROPOSED SITES

Site Summaries

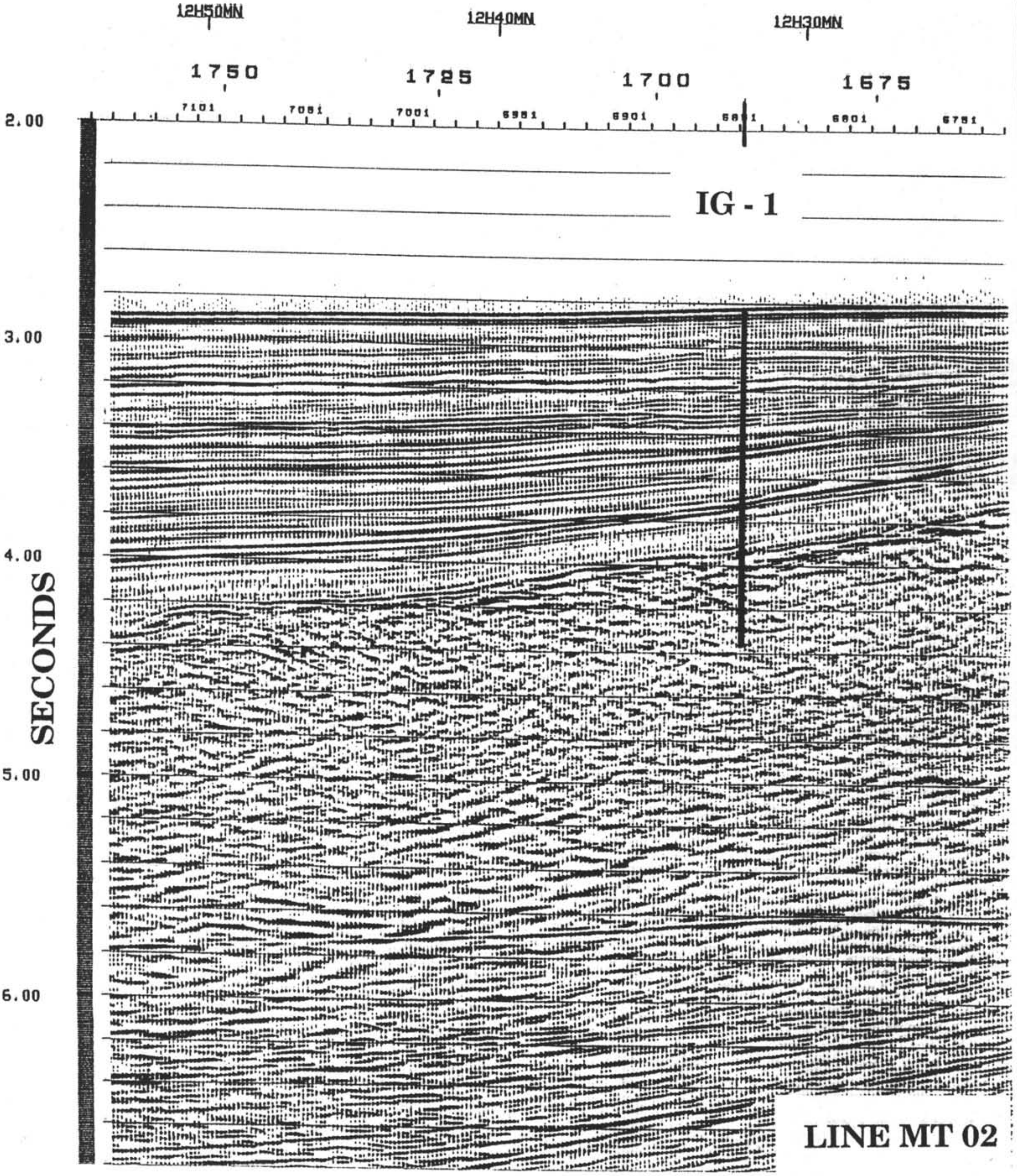


Figure 12. Enlarged section of MCS line MT02 and location of proposed site IG-1.

Site: IG-1
Priority: 1
Position: 03°37.70'N, 02°44.10'W
Water Depth: 2100 m
Sediment Thickness: >4000 m
Total Penetration: 1600 m
Seismic Coverage: MCS Line MT 02, shot point 1690

Objectives:

- To study the syn-tectonic cover and early post-rift, but syn-transform, sediments.
- To study the diagenesis, deformation history, vertical motion, and evolution of a transform marginal ridge.
- To document the Central Atlantic-South Atlantic Cretaceous and Cenozoic gateway histories.

Drilling Program: RCB to 800 mbsf, then drill reentry hole to 1600 mbsf or until drill bit destruction (approved to 1600 mbsf).

Logging and Downhole Operations: Runs with standard S, lithoporosity, and FMS tools. Heat-flow measurements within the first 300 m.

Nature of Sediment Anticipated: Pleistocene to middle Cretaceous clayey ooze and fine turbidites; Lower Cretaceous sandstones and indurated shales.

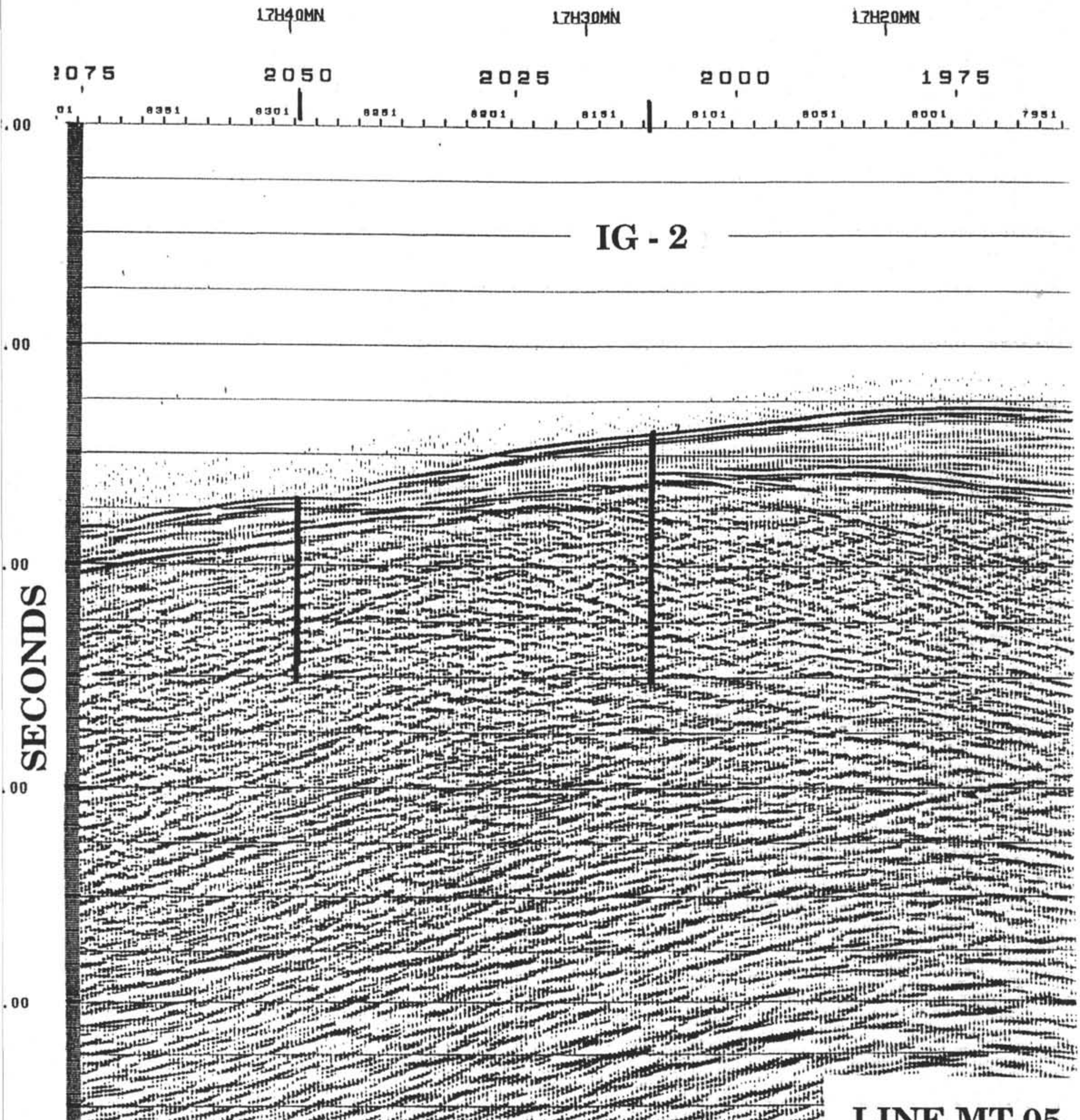


Figure 13. Enlarged section of MCS line MT05 and location of proposed site IG-2.

Site: IG-2
Priority: 1
Position: 03°26.60'N, 03°03.50'W
Water Depth: 3315 m
Sediment Thickness: >2000 m
Total Penetration: 780/800 m
Seismic Coverage: MCS Line MT 05, shot point 2010.

Objectives:

- To determine diagenesis, nature, and deformation history of a sediment wedge and potential basement that have been submitted to both syn-rift and syn-transform activities.
- To study the vertical behavior (subsidence/uplift) of a transform marginal ridge at the ocean/continent crustal boundary.

Drilling Program: RCB to 800 mbsf (approved to 800 mbsf).

Logging and Downhole Operations: Several runs including standard S, lithoporosity tools, and FMS for structural evolution of the sedimentary pile.

Nature of Sediment Anticipated: Discontinuous Pleistocene to Cretaceous clayey oozes and hardgrounds, and Lower Cretaceous sandstones, siltstones, and indurated shales.

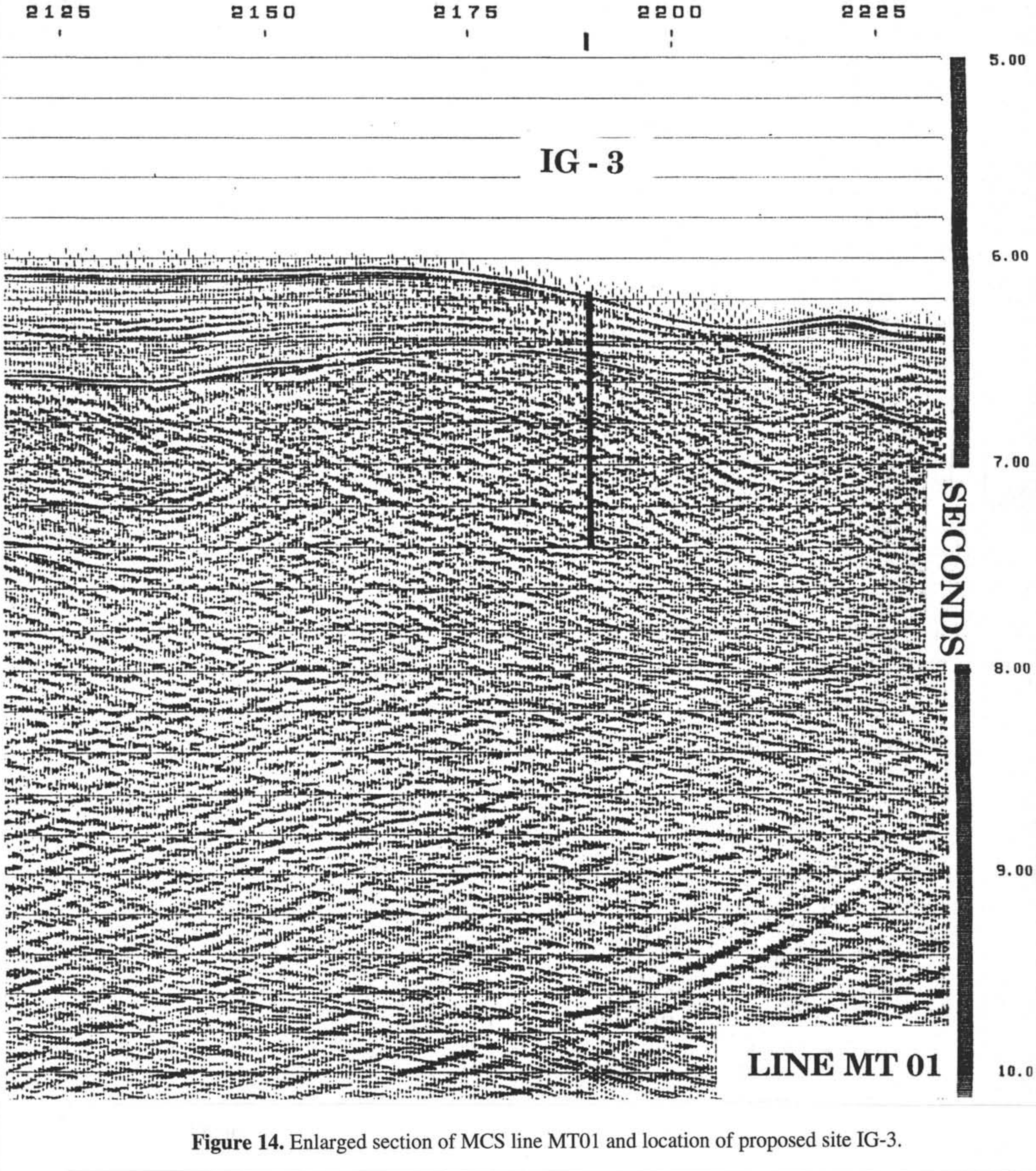


Figure 14. Enlarged section of MCS line MT01 and location of proposed site IG-3.

Site: IG-3
Priority: 1
Position: 03°15.15'N, 03°10.95'W
Water Depth: 4630 m
Sediment Thickness: >1000 m
Total Penetration: 750/800 m
Seismic Coverage: MCS Line MT 01, shot point 2190.

Objectives:

- To determine nature, deformation history of "en échelon" lower margin ridges generated in a transform setting just near the ocean/continent boundary.

Drilling Program: RCB to 800 mbsf.

Logging and Downhole Operations: Standard S, lithoporosity tools, and FMS for detailed structural studies.

Nature of Sediment Anticipated: Up to 300 m of soft oozes, resting on several hundreds of meters of indurated and deformed sandstones and other clastics.

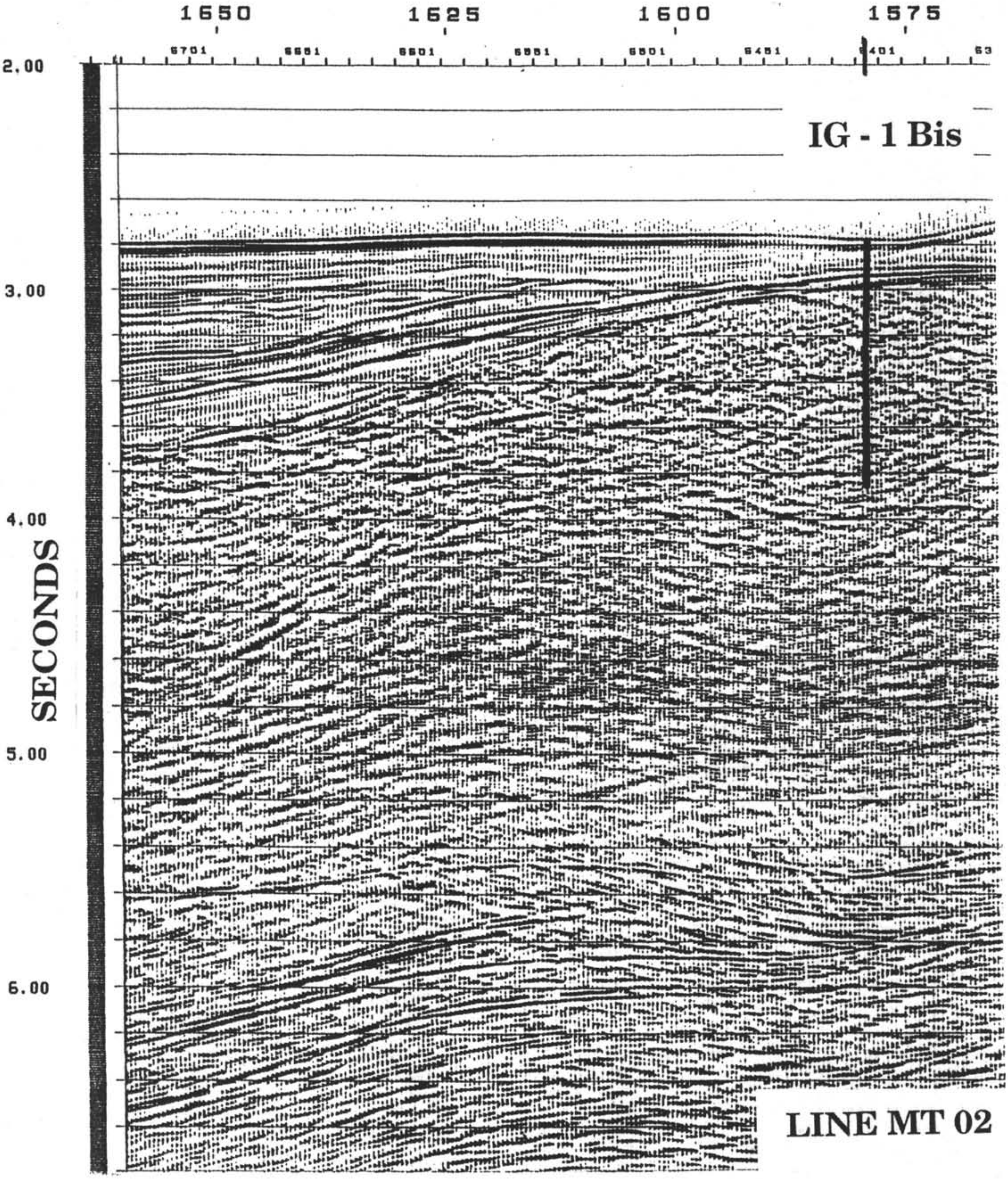


Figure 15. Enlarged section of MCS line MT02 and location of alternate site IG-1Bis

Site: IG-1bis
Priority: 2
Position: 03°35.00'N, 02°44.00'W
Water Depth: 2085 m
Sediment Thickness: Soft sediments - 200 m; clastics - >1000 m
Total Penetration: 1000 m
Seismic Coverage: MCS Line MT 01, shot point 1580

Objectives: Same as proposed site IG-1.

- To determine the nature, age, diagenesis, deformation history, and subsidence/uplift evolution of a transform-generated sedimentary wedge.
- To document the Cretaceous to Cenozoic equatorial Atlantic gateways.

Drilling Program: RCB drill until drill bit destruction. Probable reentry to reach 1000 mbsf (approved to 1000 mbsf).

Logging and Downhole Operations: Several runs including standard S, lithoporosity, and FMS (structural studies). Heat-flow measurements within the first 300 m.

Nature of Sediment Anticipated: 200 m of Pleistocene to Cretaceous nannofossil ooze, including numerous hiatuses and potential hardgrounds over several hundred meters of indurated clastics of prodeltaic to slope deltaic facies (sandstones, siltstones, and shales).

Site: IG-2B

Priority: 2

Position: 03°26.10'N, 03°04.50'W

Water Depth: 3530 m

Sediment Thickness: Unconsolidated sediments on the order of 300 m, indurated clastics up to 1000 m

Total Penetration: 500 m

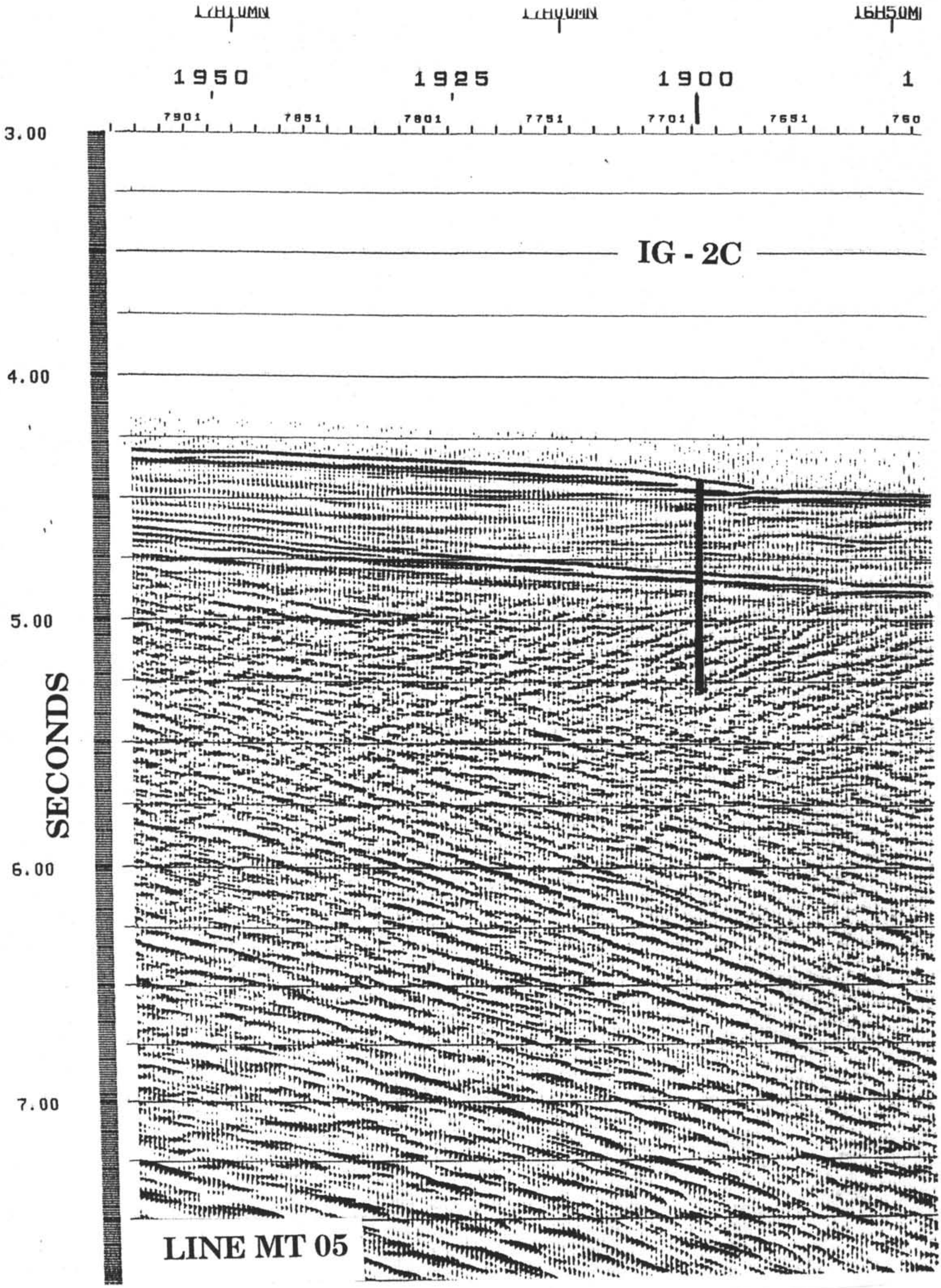
Seismic Coverage: MCS Line MT 05, shot point 2050

Objectives: Same as for proposed site IG-2. Both proposed sites IG-2B and IG-2C constitute alternate sites in case safety problems are encountered at proposed site IG-2.

Drilling Program: RCB.

Logging and Downhole Operations: Standard S, lithoporosity, and FMS runs.

Nature of Sediment Anticipated: Discontinuous Pleistocene to Cretaceous unconsolidated to semi-consolidated oozes and fine turbidites (potential hardgrounds) overlying clastics.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1950
1925
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760
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SECONDS
IG - 2C
LINE MT 05

Site: IG-2C
Priority: 2
Position: 03°27.60'N, 03°01.00'W
Water Depth: 3205 m
Sediment Thickness: >3000 m
Total Penetration: 500 m
Seismic Coverage: MCS Line MT 05, shot point 1900

Objectives: Companion site of proposed site IG-2B as alternate for proposed site IG-2 in the event of safety problems.

Drilling Program: RCB.

Logging and Downhole Operations: Standard S, lithoporosity, and FMS runs.

Nature of Sediment Anticipated: Discontinuous Pleistocene to Cretaceous pelagic oozes and fine turbidites over prograding wedge of deltaic environment.

Site: IG-3bis

Priority: 2

Position: 03°14.85'N, 03°10.80'W

Water Depth: 4725 m

Sediment Thickness: 150-200 m of soft sediments on a potential sedimentary wedge of unknown thickness (0 to 2 km)

Total Penetration: 800 m

Seismic Coverage: MCS Line MT 01, shot point 2200

Objectives:

- To determine the nature and deformation history of lowermost slope ridges that have been emplaced by transform motion near the ocean/continent boundary.

Drilling Program: RCB.

Logging and Downhole Operations: Standard S, lithoporosity, and FMS runs.

Nature of sediment Anticipated: Thin (150-200 m), discontinuous (hardgrounds) Pleistocene to Cretaceous oozes over a thick wedge of tectonized clastics (metasandstones and metasiltstones) and/or basement.

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