A geological field trip to the Côte d'Ivoire-Ghana transform margin

Transform margin
Geology
Côte d'Ivoire-Ghana
Equatorial Atlantic

Marge transformante
Géologie
Côte d'Ivoire-Ghana
Atlantique équatorial

Jean MASCLE [1], Michel GUIRAUD [2*], Jean BENKHELIL [3], Christophe BASILE [4], Jean-Pierre BOUILLIN [4], Georges MASCLE [4], Michel COUSIN [5], Marc DURAND [2], Jean DEJAX [6], Michel MOULLADE [7]

[1] Observatoire Océanologique de Villefranche, UMR 6526, Géosciences Azur, BP 48, 06235 Villefranche-sur-Mer cedex, France.
[2] Laboratoire de Géologie des Ensembles Sédimentaires, Université de Nancy (URA CNRS 157), BP 239, 54505 Vandœuvre-les-Nancy, France.
* Centre des Sciences de la Terre, Université de Bourgogne, 6 boulevard Gabriel, 21000 Dijon, France.
[3] Laboratoire de Sédimentologie et Géochimie Marines (URA CNRS 715), 52 avenue de Villeneuve, 66860 Perpignan, France.
[4] Institut Dolomieu, Université de Grenoble (ERS CNRS 129), 15 rue Maurice Gignoux, 38031 Grenoble, France.
[5] Laboratoire de Géodynamique, Université de Chambéry (ERS CNRS 129), 74000 Chambéry, France.
[6] Laboratoire de Paléontologie du Muséum National d'Histoire Naturelle (URA CNRS 12), 8 rue Buffon, 75005 Paris, France.
[7] Laboratoire de Micropaléontologie et Géologie Marines, Université de Nice (URA CNRS 327 et GDR 88), Parc Valrose, 06108 Nice, France.

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ABSTRACT

During the Equanaute survey (June 1992), fourteen submersible dives were performed between 4950 and 2250 m water depths across the southern slope of the Côte d'Ivoire-Ghana Marginal Ridge (CIGMR), in the eastern Equatorial Atlantic. The CIGMR, a high-standing topographic marginal ridge along the Côte d'Ivoire-Ghana transform margin, is believed to result from a complex structural evolution due to the specific wrench-related rifting between Western Equatorial Africa and Northeastern Brazil, in Early Cretaceous times. In this paper we report and discuss geological observations made during dives, and sample analyses to resolve the lithology, paleoenvironmental conditions, age and origin of the CIGMR. The data help in better characterizing the different sedimentary and tectonic regimes which successively prevailed during the CIGMR formation and assessing the thermal regime operative during the fabrication and subsequent evolution of the margin. The thick sedimentary pile exposed along the southern CIGMR slope is made up of a repetitive clastic sequence indicative of a deltaic-to-prodeltaic environment. This sedimentary pile, of Early Cretaceous age, has recorded different stages of the transform margin structural evolution.
(1) Syn- to post-lithification deformations first record extensional deformations related to the rifting of the adjacent northern divergent margin segment (the Deep Ivorian Basin).
(2) Wrench tectonics has, at a later stage, produced intense fracturing and participated in local folding, chiefly detected upslope. The integrated studies of geological samples and *in situ* observations obtained during the Equanaute survey support models for transform margin evolution proposed mainly from geophysical data. © Elsevier, Paris.

RÉSUMÉ

Analyse *in situ* d'un segment de marge transformante: plongées scientifiques sur la marge de Côte d'Ivoire-Ghana.

Au cours de la campagne Equanaute (juin 1992) quatorze plongées, effectuées à bord du *Nautile* entre 4950 et 2250 mètres de profondeur, ont permis d'étudier la pente méridionale de la Ride de Côte d'Ivoire-Ghana (Atlantique équatorial). Cette Ride, qui constitue le long de ce segment de marge un relief linéaire important, est le résultat d'une évolution structurale spécifique liée à un rifting de type transformant entre Afrique de l'ouest et Nordeste brésilien au cours du Crétacé inférieur.
Dans cet article nous décrivons et discutons les résultats géologiques provenant à la fois des observations en plongées et des études sur les échantillons géologiques récoltés. Ces données permettent de mieux comprendre les conditions du paléoenvironnement, l'âge et les différents épisodes tectoniques actuellement enregistrés dans les sédiments indurés affleurant tout au long de la pente observée. Les résultats permettent aussi d'évaluer les conditions thermiques contemporaines de la création de la Ride marginale, puis de son évolution ultérieure. L'épaisse série sédimentaire terrigène est, pour l'essentiel, constituée de dépôts cycliques vraisemblablement déposés dans un environnement de type deltaïque et de prodelta.
Cet ensemble sédimentaire, d'âge Crétacé inférieur, a enregistré différents épisodes de déformation: une déformation, contemporaine de la lithification, apparaît caractéristique d'un régime extensif accompagnant la création du segment de marge divergent voisin, l'actuel bassin profond de Côte d'Ivoire. Une déformation de type cisaillant a, par la suite, produit une importante fracturation et a abouti localement à la mise en place de plis, décelables surtout vers le haut de la pente explorée. Ces résultats d'ordre géologique sont en bon accord avec un modèle d'évolution de la marge transformante déduit de données géophysiques recueillies antérieurement.

NOTE

Cet article, synthèse d'observations géologiques provenant de plongées du Nautile *en 1992, a été rédigé avant la réalisation de la campagne ODP 159 (1995). Les auteurs n'en ont pas modifié la teneur dans la mesure où leurs observations et conclusions ne sont en rien contredites par les résultats de cette campagne de forage.*

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INTRODUCTION

Compared with volcanic or divergent continental margins, which also result from continental break-up, transform margins show many specific characteristics. They include: (a) a very rapid ocean-continent transition (of the order of a few kilometres); (b) a complex history of uplift and subsidence; (c) a tectonic history influenced by transform motion between two breaking plates; (d) a high input of clastic sediments as a consequence of rapid subsidence and active transform tectonics; (e) a subsequent sedimentation strongly triggered by structural damming effects (Mascle and Blarez, 1987).

One of the best examples of transform margins extends off Equatorial Africa, between the Côte d'Ivoire and eastern Ghana (Fig. 1). There, the Côte d'Ivoire-Ghana Continental Margin is a consequence of major transform motions between the African and Brazilian continental lithospheres in Early Cretaceous times (Mascle, 1976; Basile *et al.*, 1993). Today, the transform motion between the two plates is still active within the Equatorial Atlantic, along the Romanche Fracture Zone which offsets the Mid-Atlantic Ridge by almost 1000 km (Honnorez *et al.*, 1991) (Fig. 1).

A quite complete set of marine geological and geophysical data has already been obtained on this transform margin segment (Basile *et al.*, 1996), including noteworthy data concerning its sedimentary records and tectonics (Mascle *et al.*, 1988; Basile *et al.*, 1993). However, detailed geological data, relating for example to sediment types, as well as information on environmental conditions, deformation styles and precise dating were very scarce and insufficient to help in better substantiating transform margin evolutionary processes.

In June 1992, during the Equanaute cruise, the Côte d'Ivoire-Ghana Marginal Ridge (CIGMR) was surveyed by the deep-sea submersible *Nautile* from IFREMER, operating from the R.V. *Nadir*. The area of investigation was focused on the steep CIGMR southern slope (Fig. 2). Today a high-standing morphologic feature, the CIGMR

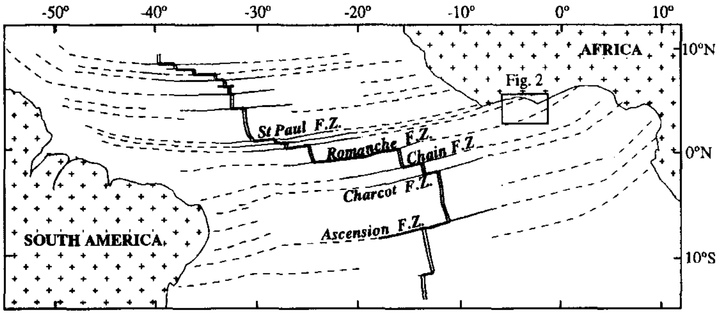


Figure 1

Sketch of the Equatorial Atlantic fractures zones and associated continental margins. The continental margin off the Côte d'Ivoire and Ghana are genetically associated to the Romanche Fracture Zone. The dotted box locates the Côte d'Ivoire-Ghana transform margin area.

is thought to represent a wrench-tectonically deformed sediment wedge, located in sharp transition between an extensional margin (the Deep Ivorian Basin) to the north and the southern oceanic crust (the Gulf of Guinea abyssal plain) (Fig. 2). The setting of the present-day Marginal Ridge includes a fossil buried ridge that connects laterally, towards the south-west with the extinct Romanche Fracture Zone, and towards the north-east with the steep Ghanaian slope (Blarez, 1986; Mascle *et al.*, 1988; Basilc *et al.*, 1993). In this paper, we present and discuss, in the light of previous geophysical results, a synthesis of collected data and subsequent analyses, and propose a reconstruction of the sedimentary and deformational histories of the CIGMR. The data have been collected during 14 deep dives performed between water depths of 4950 and 2250 m (Mascle *et al.*, 1994) (Figs. 3, 4). A total of 80 hours of *in situ* observations and continuous video records allowed the construction of 14 geological cross sections. These observations were completed by the recovery of 165 rock samples (including a few *in situ* oriented) retrieved along a total distance of about 75 km visited on the sea floor (Mascle *et al.*, 1994).

The main objectives of the deep dive Equanaute survey were: (1) to collect rock samples across the CIGMR steep southern slope in order better to resolve its lithology, ascertain its nature and determine its age; (2) to characterize the successive tectonic regimes which contributed to generate the CIGMR (extensional, wrench tectonics, gravitational collapse); (3) to assess the past thermal regime which may have likely been operating and recorded within the CIGMR sediment pile as a consequence of its proximity to the oceanic crust.

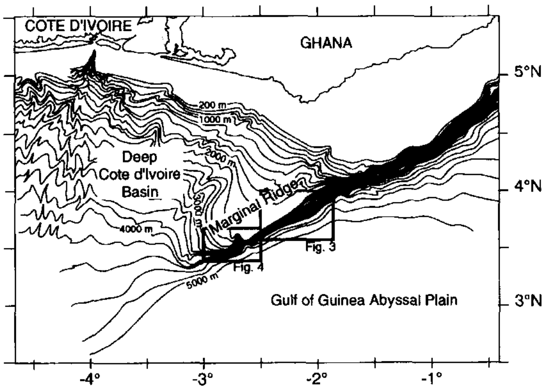


Figure 2

General bathymetric map of the Côte d'Ivoire-Ghana margin; contour lines in metres (after Blarez, 1986). Boxes locate Figures 3 and 4.

GEOPHYSICAL AND GEOLOGICAL SETTING OF THE CIGMR AND SURROUNDING AREAS

Bathymetry

A general bathymetric map of offshore Côte-d'Ivoire and Ghana (Blarez, 1986) (Fig. 2) shows several morphologic domains. These are from north to south: (a) a relatively narrow continental shelf (only a few kilometres off Côte d'Ivoire to about 70 km off Ghana; (b) a well developed continental slope and rise known as the Deep Ivorian Basin; (c) the prominent (up to 2010 m depth) South-west to north-east trending CIGMR, which bounds towards the southern most point of the Ivorian Basin and rises, locally by more than 3000 m, above the adjacent southern Gulf of Guinea Abyssal Plain (5000 m depth on average). Eastwards, the ridge connects with the very steep Ghanaian continental slope, while towards the south-west it progressively deepens and passes to a series of aligned small-scale abyssal hills, on a trend with the fossil Romanche Fracture Zone.

Detailed swath bathymetric maps collected during a previous survey (Mascle *et al.*, 1989), cover respectively the CIGMR eastern corner, most of the CIGMR itself and parts of the adjacent Deep Ivorian Basin (Figs. 3, 4). On morphological grounds the investigated slope can be divided, from east to west, into four distinct domains: (a) An eastern domain exhibits, between 2000 and 4000 m water depth, a rather gentle slope (20° on average) dissected by several normally sloping valleys. Equanaute dives EN01 to EN03 (Fig. 3) were made across these valleys. The area is almost entirely covered by thin recent muddy sediments and only upslope shows a few rocky scarps where outcrops have been observed and sampled; (b) A central domain, disconnected from the previous one by a deep cross-cutting canyon. In this area, the steep slope is almost rectilinear and very regular, N65° E trending, and has been investigated by Equanaute dives EN04 to EN06 and EN11 (Fig. 3). The slope averages 50° and locally vertical cliffs exist; (c) A third slope domain lies just south of the marginal ridge top, which culminates at 2010 m water depth (Fig. 4). In this area the slope is cut by several very steep, north-south trending promontories. Equanaute

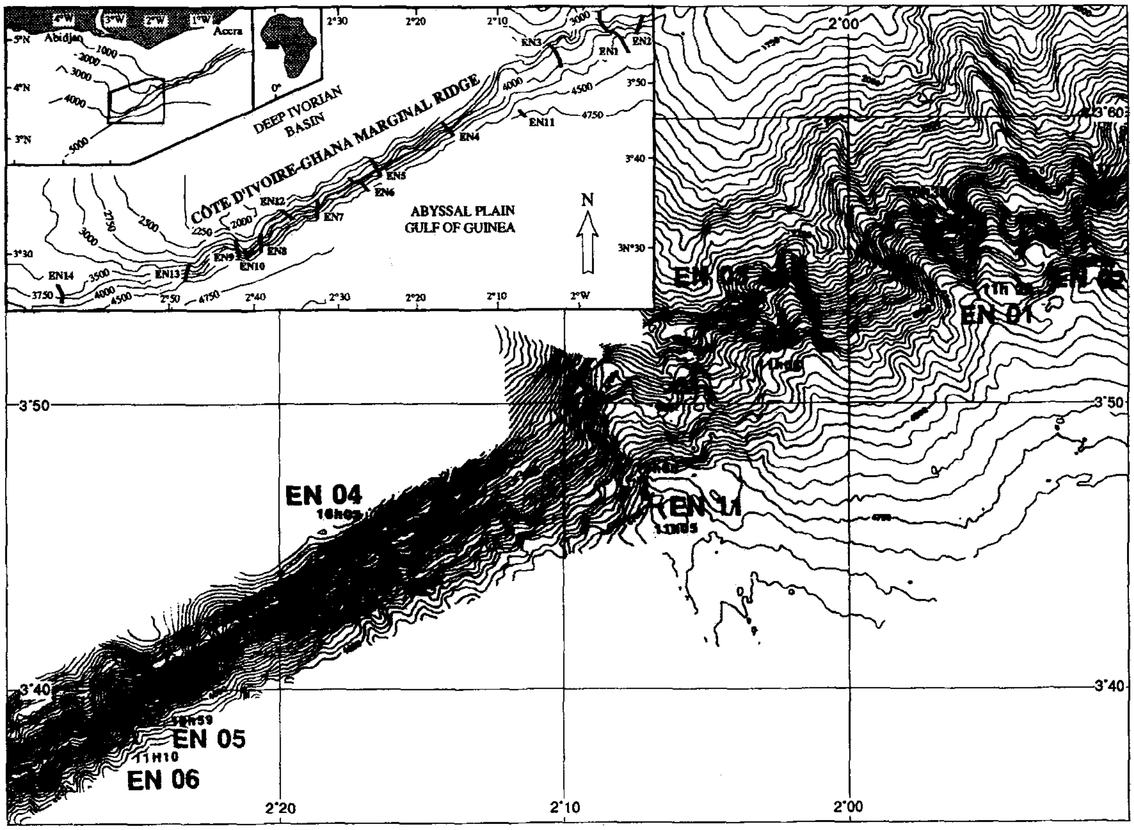


Figure 3

Location of Equanaute deep dives along the eastern and central domains of the Côte d'Ivoire-Ghana Marginal Ridge. The dives were performed between 4600 m and 2500 m water depth. About 5 to 6 km of sea floor was visited and 12 to 15 in situ *rock samples were retrieved during each dive.*

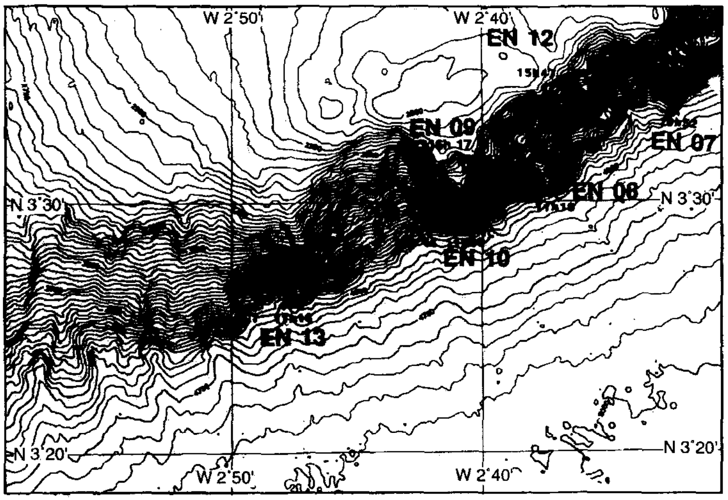


Figure 4

Location of Equanaute dives along the southwestern domain of the CIGMR. The dives were performed between 4300 m and 2250 m water depth.

dives EN07 to EN10 and dive EN12 have documented, near the slope foot, huge rocky chaos (made of blocks several metres to tens of metres in size) and, upslope, impressive vertical cliffs; (d) Lastly, Equanaute dives EN13 (Fig. 4) and EN14 (insert Fig. 3) visited the CIGMR south-western corner, where the average slope is less accentuated (20 °), due to an increasingly soft sediment thickness and to the progressive CIGMR deepening.

CIGMR seismic stratigraphy

Prior to the deep dives, the seismic stratigraphy of the CIGMR and surrounding areas was established on the basis of a dense set of single-channel and multichannel seismic (MCS) reflection data (Blarez, 1986; Mascle *et al.*, 1988; Basile, 1990; Basile *et al.*, 1993; Basile *et al.*, 1996). The good resolution and short spacing of these lines permitted detailed analysis and mapping of the successive sedimentary records of the Deep Ivorian Basin and bordering CIGMR shoulders. More penetrative MCS lines have, in particular, demonstrated the CIGMR to be made up of a thick pile of deformed sediments, with interval velocities of the order of 3.6 km/s (Basile *et al.*, 1996; Lamarche *et al.*, 1997). Such velocities imply a sedimentary thickness locally in excess of 3 to 4 km, as also supported by wide-angle seismic data (Sage, 1994; Mascle *et al.*, 1995). Beneath both the CIGMR and its northern bordering basin, several acoustic units have been distinguished (Fig. 5):

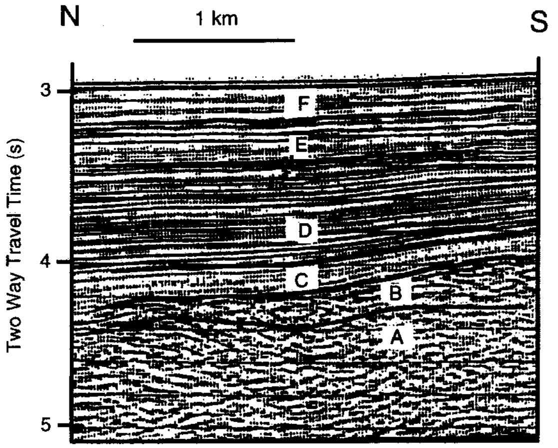


Figure 5

Main litho-acoustic units as defined by Basile et al. *(1993) within the Deep Ivorian Basin and along the northern slope of the Marginal Ridge. ODP Leg 159 (Mascle* et al., *1995) has allowed identification of these units as Early Cretaceous (B), Late Cretaceous to Paleocene (C), Eocene (D), Oligocene (E) and Miocene to Quaternary (F) in age.*

(1) A basal unit, referred to as unit A, constitutes the synrift infilling of half-grabens detected beneath most of the deep extensional Ivorian Basin; unit A usually shows a contrasted and continuous acoustic facies but displays a chaotic and discontinuous acoustic character nearby and within the CIGMR. Apparently directly exposed along the ridge southern slope, this formation is believed to constitute most of the ridge sedimentary pile. MCS profiles across the CIGMR indicate that this unit can be subdivided into three subunits (A0, A1, A2) bounded by successive unconformities (Lamarche *et al.*, 1997).

(2) In the Deep Ivorian Basin, an overlying and unconformable unit B represents the first post-rift sedimentary cover (Fig. 7*a*). Along the ridge top, this unit may locally thicken considerably. Unit B, being postrift in the extensional domain and clearly deformed in the vicinity of the marginal transform ridge, has been referred to a "syntransform" unit, coeval with the CIGMR main transform tectonic stage (Basile *et al.*, 1993). Recently Leg ODP 159 has demonstrated the clastic nature of this unit and provided an Albian age for its upper section (Mascle, Lohmann, Clift *et al.*, 1996).

(3) The overlying units C to F, respectively of Late Cretaceous, Paleogene, Neogene and Miocene to Quaternary age (Mascle, Lohmann, Clift *et al.*, 1996), are only affected by gravitational sliding and/or differential compaction deformations within the Ivorian Basin. They are either onlapping the ridge slope (units C and D) or directly the ridge crest (units E and F). Their respective arrangement is thought to reflect various CIGMR vertical movements (uplift and subsidence) throughout time.

Tectonics

Within the Deep Ivorian Basin, extensional features such as half-grabens and asymmetric horsts are well imaged on MCS lines. Tilted blocks are 4-5 km wide (Sage, 1994; Basile *et al.*, 1996), comparable to those described in many divergent margin segments. The CIGMR is itself characterized by wrench tectonics with variable along-strike deformations. Near its connection with the Ghanaian platform, the transform zone is expressed by reverse faulting and associated *en echelon* gentle folds (Fig. 6, 7*b*). From 2° 10′ W to 3° 15′ W, the structural ridge is expressed by a N65° trending acoustic basement-like high, which progressively deepens and shifts towards an east-west direction. MCS data also clearly demonstrates that the CIGMR is cut in a series of extensional rotated blocks quite similar to those of the neighbouring northern Ivorian basin (Basile *et al.*, 1996; Lamarche *et al.*, 1997) (Fig. 7*c*). Wrench-fault lineaments are less easy to detect since they were probably activated as sub-vertical features cross-cutting clastic, and already deformed materials (Basile *et al.*, 1989; Popoff *et al.*, 1989) (Fig. 6). However, MCS line MT01 (Fig. 7*d*) shows that near its western end, the fossil transform is still expressed as a buried, 10 km wide complex flower-type structure. Finally, west of 3° 10′ W, close to the oceanic abyssal plain, the marginal ridge vanishes and passes to a series of *en echelon* minor ridges, some 10-15 km in length, a few kilometres wide and less than 500 m in elevation. Further west, these almond-shaped bodies connect with aligned acoustic basement highs which denote the fossil Romanche Fracture Zone (Fig. 6).

Lithology and dating

Before the Equanaute dives, very few samples were recovered along the transform margin southern slope by piston coring or dredging (Blarez *et al.*, 1987). All consisted of sandstone or siltstone, with the exception of a few quartzites assumed to be of Paleozoic age (Mascle and Smit, 1974) and a black shale-type claystone. None of these samples could be correlated with the different seismic units. However, calcareous sandstones, presumably pertaining to A or B units, yielded an ostracod fauna of late Albian age (Grosdidier, oral comm.), while a piston core, retrieved from the CIGMR top, indicated a middle Albian shallow marine environment (Klingebiel, 1976). Recent ODP drilling operations have shown that most of

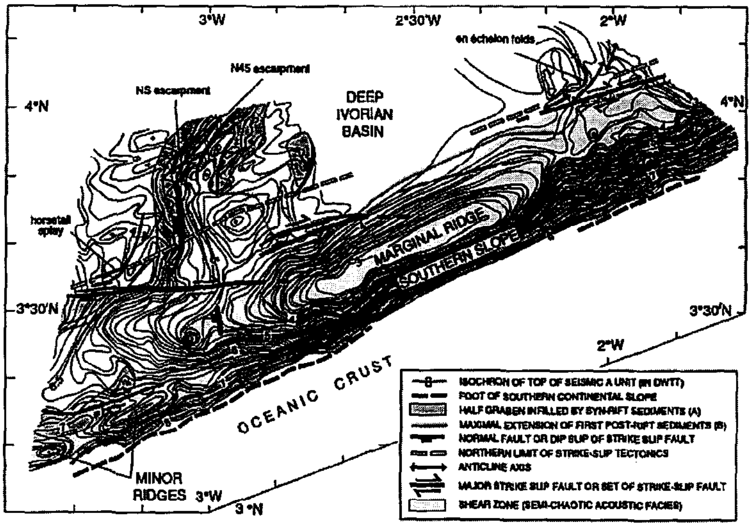


Figure 6

Structural sketch of the Côte d'Ivoire Marginal Ridge and surrounding areas (modified after Basile et al., *1993). Depth is given in two-way travel time (seconds) to the top of the deformed sediments (units A and B).*

the CIGMR consists of early Cretaceous clastics (lacustrine to prodeltaic sediments), covered unconformably by thin late Cretaceous open marine sediments and condensed Cenozoic deposits (Mascle *et al.*, 1996).

DEEP DIVE RESULTS

Deep dives show that a sedimentary section is almost continuously exposed along the CIGMR southern slope.

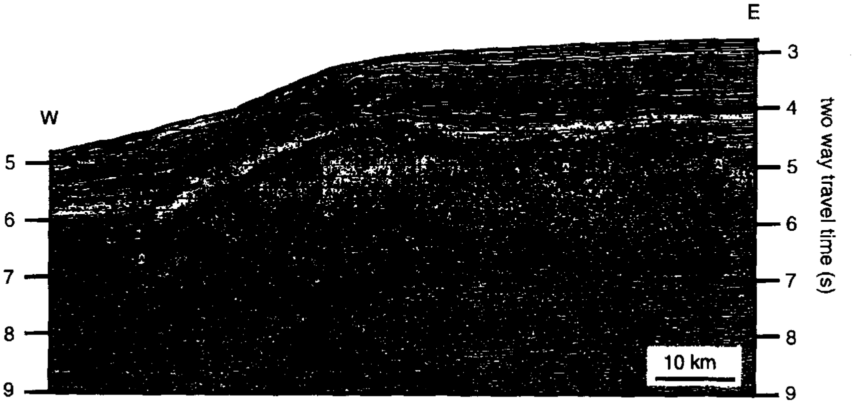


Figure 7*a*

Example of an east-west MCS migrated section across the Deep Ivorian Basin. The section shows a series of rotated blocks bounding half-grabens infilled by the A unit. The break-up unconformity is located between units A and B.

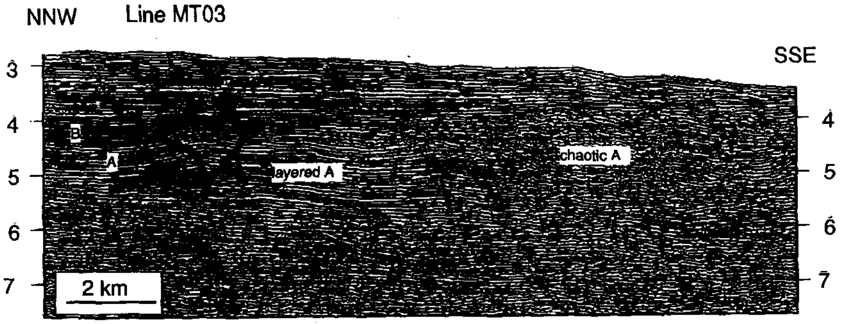


Figure 7*b*

Example of a migrated MCS section across the eastern transform domain nearby its contact with the Ghanaian Platform. Note the reverse faulting which has deformed the lower units within the proximal Ivorian Basin.

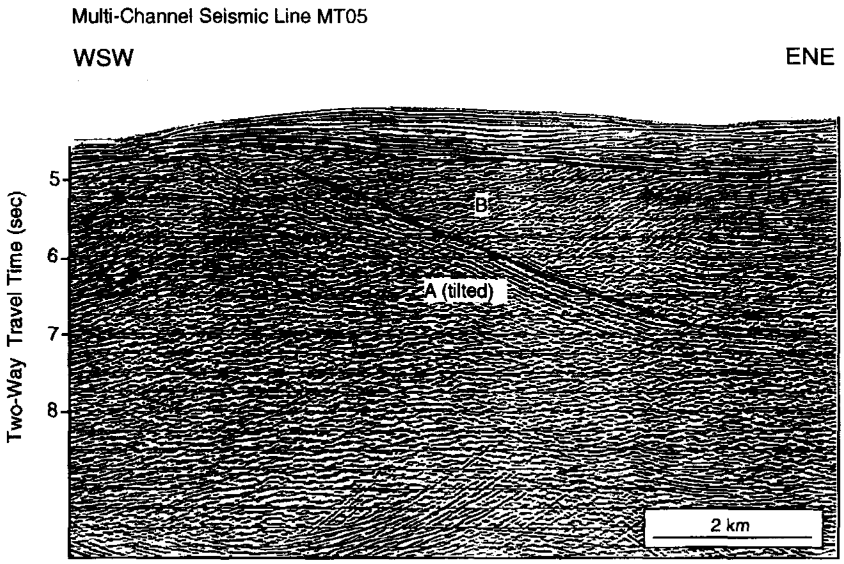


Figure 7c

Example of a migrated section over the ridge top. The section illustrates a rotated block and its bordering half graben. Unit A infills the graben, and is covered unconformably by the unit B, itself onlapped by post-tectonic sedimentary sequences.

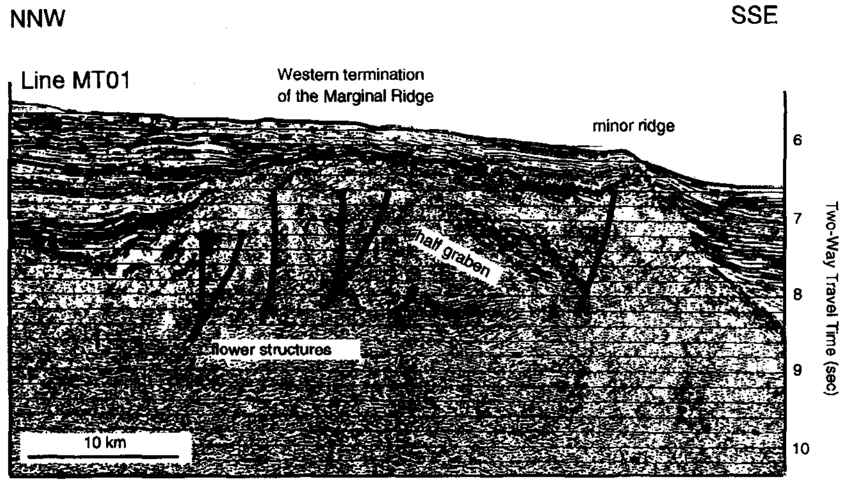


Figure 7d

Example of a migrated MCS section across the westernmost and buried extension of the Marginal Ridge. The western termination of the ridge appears deformed in a set of positive flower structures. Southward, a minor ridge is emplaced near the continent-ocean boundary.

Its lithology and structure have been well characterized by direct observations, continuous video records and over 2000 colour photographs, as well as by analyses of hand-sized polished slabs and thin sections made on most of the 165 retrieved samples. Dating still remains difficult since the recovered sediments were found almost barren of microfossils (see below).

LITHOLOGY AND AGE OF THE CIGMR SEDIMENTARY SECTION

Lithofacies

A lithofacies reconstruction was attempted by Guiraud *et al.* (1997a), combining studies of *in situ* outcrop attitudes and rock sample observations from several selected representative dives. Direct *in situ* observations and video records from most of the other dives have, however, been taken into account to determine distinct morphological features, clearly related to three major lithofacies (Mascle *et al.*, 1993). We have thus attempted: (a) to establish an accurate lithology of exposed rocks for each different slope domain; (b) to characterize the main lithofacies associations; (c) to better assess the paleoenvironmental conditions coeval with the successive tectonic stages of the CIGMR formation.

For the northeastern CIGMR domain, we selected dives EN01 and EN11 (Fig. 4), whereas the central and southwestern areas were analysed using dives EN04 to EN06 and dives EN12 to EN14 respectively (Figs. 3, 4). In all dives, the slopes consist of alternative gentle benches, mud and scree draped or encrusted, interrupted by 40-80° steep scarps. Thinly laminated dark or yellowish fine-grained rocks (claystones), which represent Facies 1, are occasionally exposed along these benches. The numerous outcrops along the steep scarps reveal three other lithofacies. Facies 2 is expressed by 5–40 m high walls (Plate I) including medium-scale trough cross-beds, 0.2-2 m thick. The highly fractured scarps formed by Facies 3

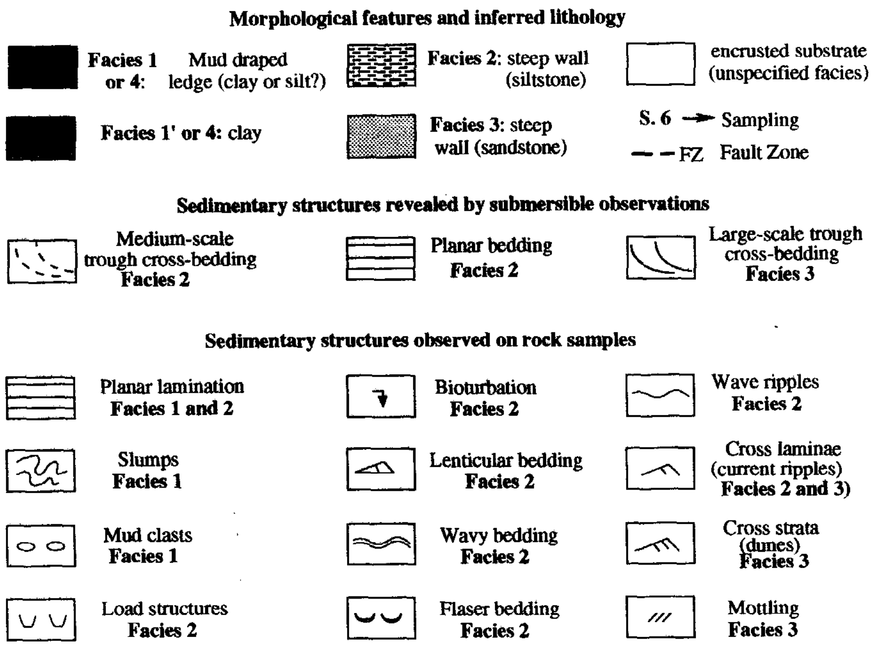


Figure 8*a*

Main symbols used for representation of clastic deposits of Figures 8b, *9, 10.*

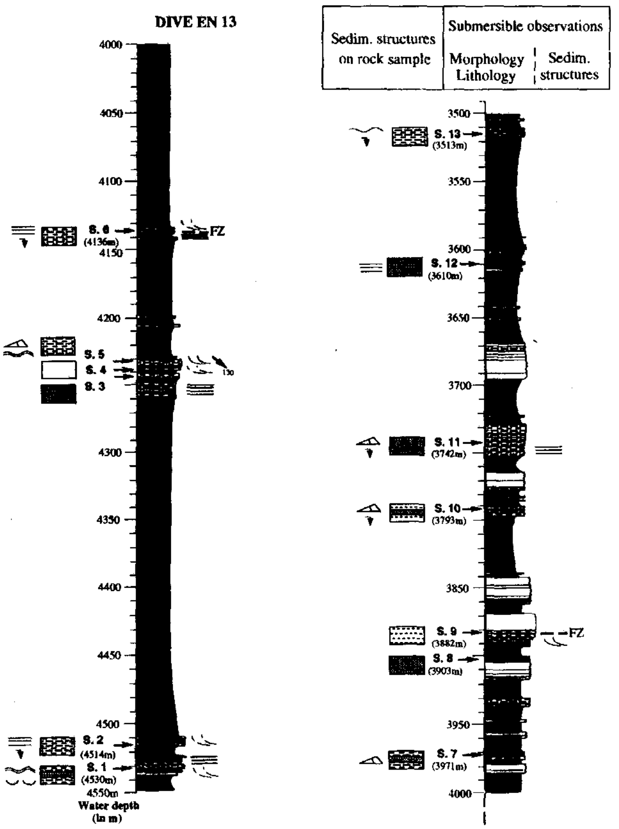


Figure 8*b*

Example of a lithologic log reconstructed from observations and sampling during dive EN13 (after Guiraud et al., *1997*b*); S1 to S13 refer to sample locations.*

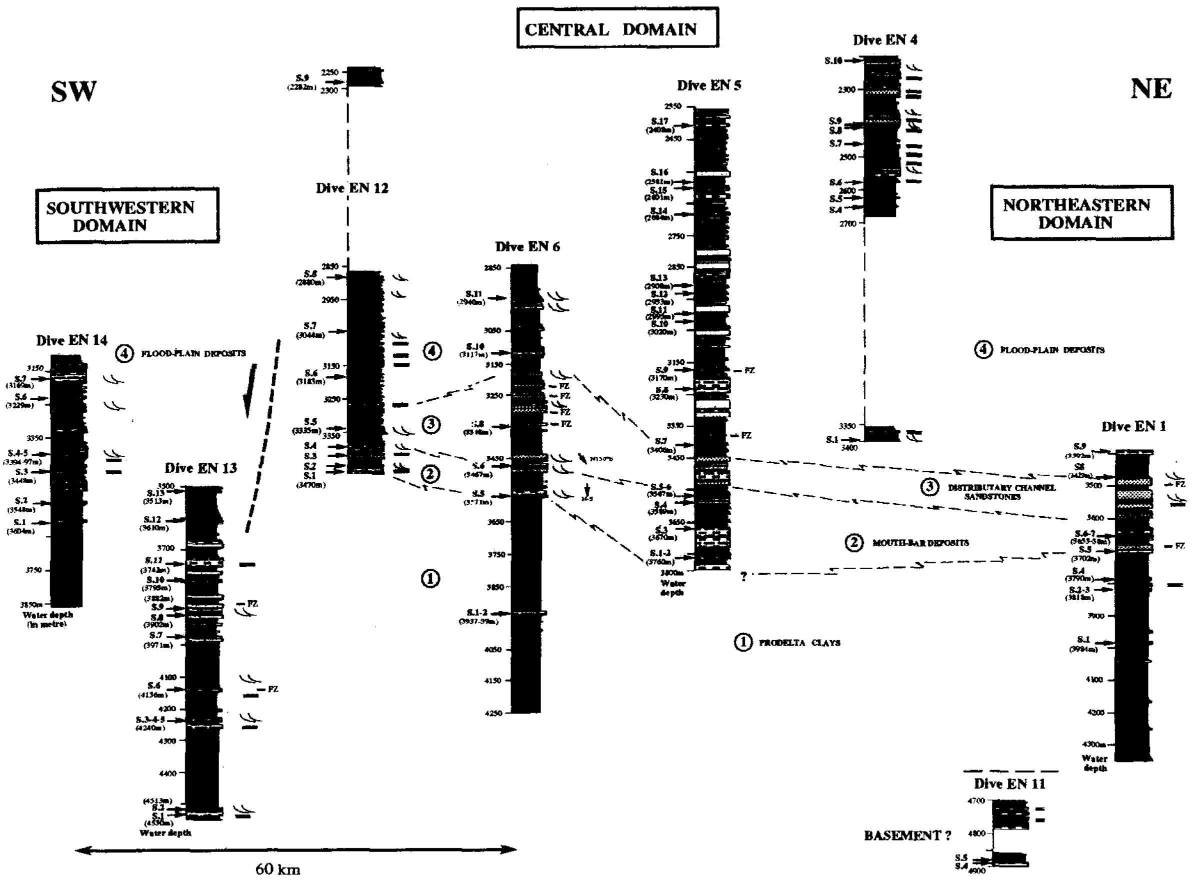


Figure 9

Reconstructed lithological logs of clastic sections (syn-rift to syn-transform deposits) both outcropping along the northeastern, central and southwestern CIGR domains (see *location on Figs. 3, 4). 1, 2, 3, 4 refer respectively to sections where prodelta clays, mouth-bar deposits, distributary channel sandstones and flood plain deposits are respectively predominant. An attempt of correlation along the CIGMR slope is shown by dotted lines.*

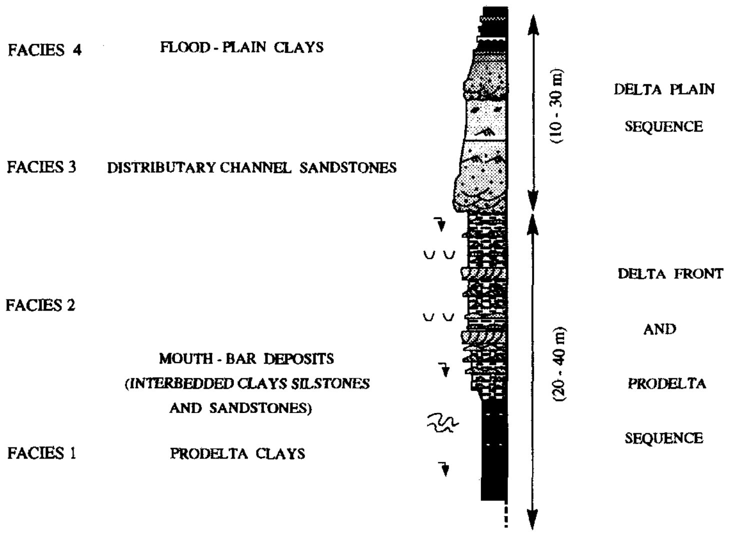


Figure 10

Synthetic sedimentary sequences of clastics exposed along the marginal ridge southern slope as deduced from integration of dive observations and in situ *sampling.*

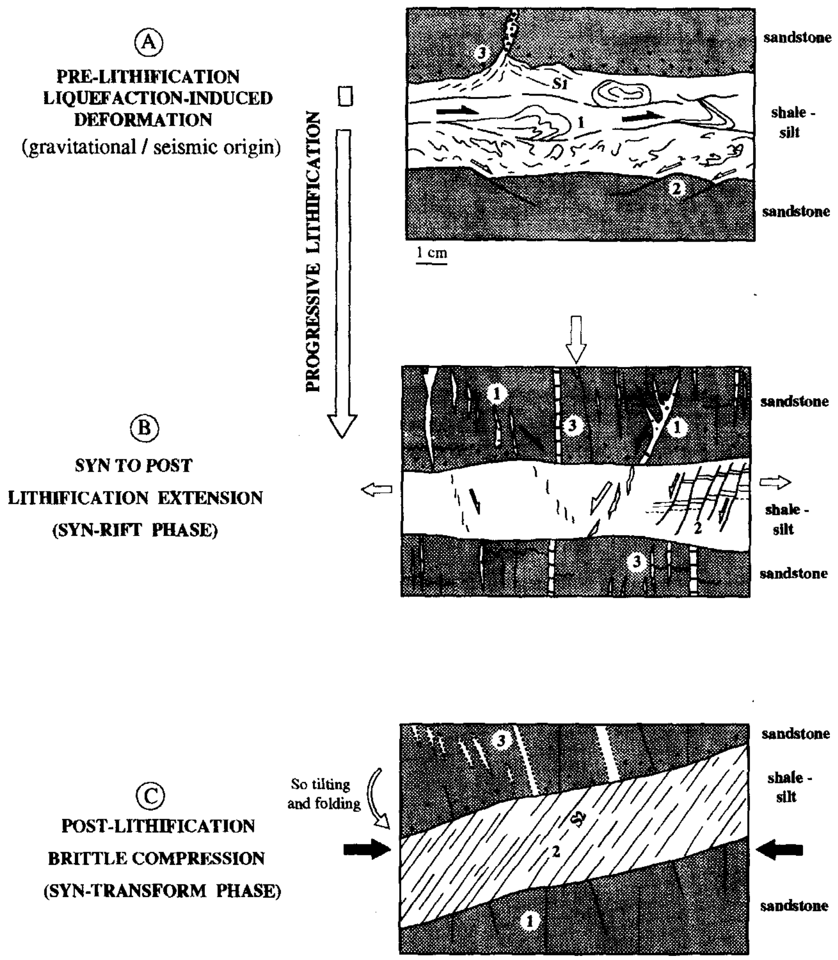


Figure 11

Summary of the deformational history of the CIGMR as observed on samples. The characteristic sediment sequence consists of laminated siltstones and shale interbedded with sandstones and rare gravel casts.
A: Pre-lithification liquefaction-induced microstructures: type 1 - Tight to disharmonic isoclinal slump microfold and associated sliding bedding planes; type 2 - Listric normal microfaults; type 3 - Mud pipe with fan-shaped hydroschistosity (S1).
Syn to post-lithification extensional microstructures: type 1 - syn-lithification normal to bedding quartz vein; type 2 - pervasive normal syn-lithification microfaults; type 3 - post-lithification normal to bedding quartz vein.
C: Late brittle wrench microstructures: type 1 - vertical brittle joint; type 2 - slaty cleavage S2; type 3 - tilted extensional microstructures.

vary from 10 to 40 m in elevation, and are generally in basal sharp contact. They show large-scale trough cross-bedded sets (2-4 m thick) grading up into massive layers of about one metre in thickness (Plate I).

Almost all the recovered samples are of siliciclastic nature and belong to the same siltyclay-to-sandy formation. Facies analysis has been proposed on the basis of sedimentological critera (lithology, texture and biological microstructure) as shown in Figure 8*a*.

The few retrieved Facies 1 samples consist of black shales, dark organicmatter-rich clays and thinly-laminated bioturbated siltstones, generally affected by numerous synsedimentary deformations (see further). Locally, this facies may appear as massive outcrops, but it commonly displays diffuse parallel beds related to slight grain-size variations. A carbonate claystone from dive EN01A indicates the local influence of a more open marine environment.

Facies 2 corresponds to wavy-bedded yellowish siltstones and claystones alternating with lenticular to flaser-bedded greenish fine-grained sandstones, frequently bioturbated. Subordinate components are well-sorted siltstones and fine-grained sandstones usually displaying prominant symmetrical ripples and parallel laminations.

Facies 3 includes yellowish, fine to coarse-grained feldspathic and micaceous graded sandstones. Thin micro-conglomeratic beds are observed over basal erosional surfaces. They grade up into poorly sorted to faintly cross-

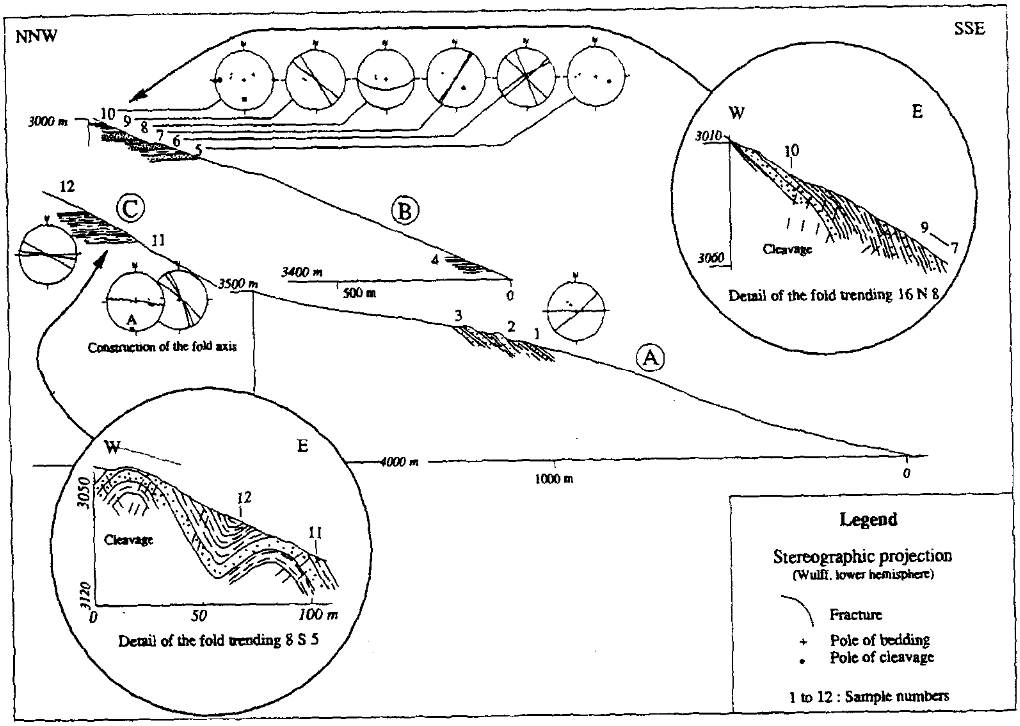


Figure 12*a*

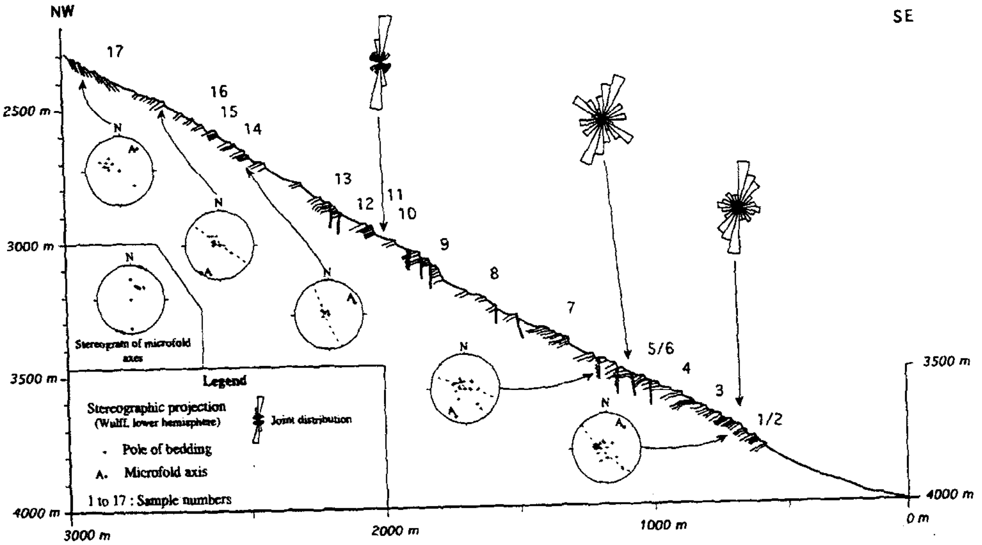


Figure 12*b*

bedded massive sandstones. A few greenish fine-grained sandstone beds display mottling structures and suggest subaerial exposure.

Finally, a Facies 4 corresponds to massive, mottled fine-grained sandstone beds covered by yellowish siltstone layers, and thinly laminated and organic matter-rich claystones. These sandstones often show an upward decreases in cross-set thickness.

Biostratigraphic and fission track dating

Dating Equanaute retrieved samples remains an outstanding problem, since the entire section appears almost barren of foraminifers and nannoplankton. Until now only very few samples, chiefly from dive EN01 (Fig. 3), have yielded marine microfauna. A carbonate claystone from this dive indicates a time span between Barremian and

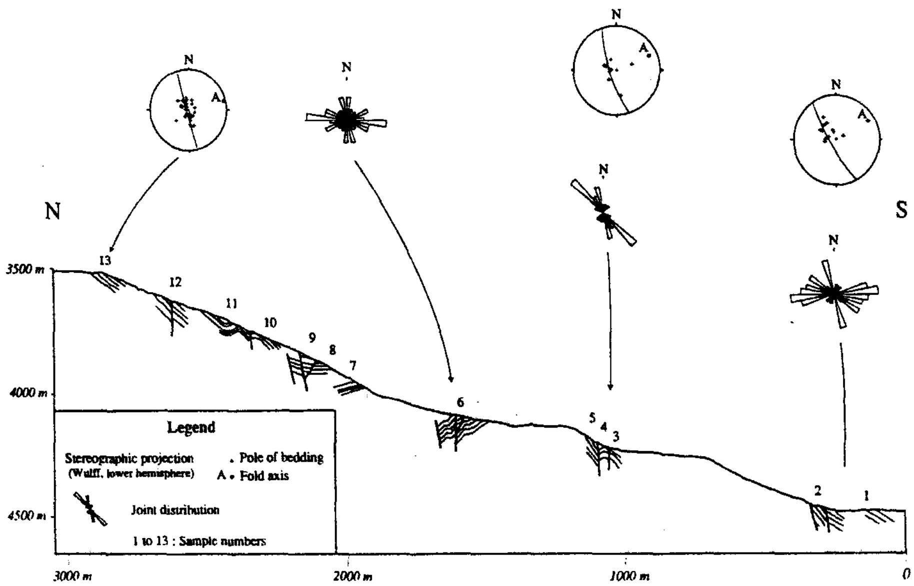


Figure 12c

Examples of synthesis of structural and microtectonic observations made during dives EN03 (Fig. 12a), EN05 (Fig. 12b) (location on Fig. 3) and EN13 (Fig. 12c) (location on Fig. 4); stereographic projections of bedding planes (S0) and plotting of the joint directions on rose diagrams are shown.

early Cenomanian (more likely Albian) on the basis of tiny and poorly preserved planktonic foraminifers. Palynologic assemblage studies, still in progress, seem more promising. For example, the palynological analysis of sample 11 (from EN03 dive) has yielded a microflora shed by terrestrial plants. This assemblage is dominated by conifer pollen grains (genera *Araucariacites* and *Classopollis*), then by fern spores (genera *Cicatricosisporites, Leptolepidites, and Dictyophyllidites*). Genus *Afropollis* and species *Elaterosporites verrucatus* [Jardiné and Magloire, 1965] (Jardiné, 1967), permit us to assign an age between middle to late Albian to this sample (Jardiné, 1967). Dinoflagellate cysts are also noticeable: their occurrence confirms a marine influence during the deposition of sediments, whose palynological content clearly reveals a continental origin. A preliminary attempt has been made to date the sediments using fission track analysis on apatite and zircon minerals from coarse-grained sandstones (Bouillin *et al.*, 1994). New data available from detrital apatites clearly indicates heating above 120 °C. The following ages have been obtained for cooling below the 60 °C isotherm: 83 Ma (sample 8 dive EN01, 3479 m water depth); 69 Ma (sample 9 dive EN04, 2405 m water depth); 68 Ma (sample 5 dive EN06, 3571 m water depth); 78, 90 and 92 Ma (dive EN09, at 2673, 3524 and 3905 m water depth respectively). These values tend to support two distinct thermal events: an older one, around 90 Ma, may be tentatively related to heating during intracontinental transform fault activity; a second one, between 70 to 80 Ma, may be correlated to heating by the passing the southern oceanic spreading centre, during the latest Cretaceous (Bouillin *et al.*, 1997).

Depositional environment

Based on dive observations and sample lithofacies studies, the lithological log of dive EN13 (Fig. 8*b*) has been selected as an example to present and discuss the vertical facies relationships observed across most of the investigated sections. For this reconstruction, we assumed elementary scarp elevations to be representative of sedimentary unit thickness, since the rocks were only gently dipping. The resulting composite sedimentary section appears to be more than 1000 m thick and includes cycles of alternating Facies 1 and Facies 2 deposits. Whereas claystones (Facies 1) seem to contribute up to 80 % of the lower section, siltstones (Facies 2) are prevailing on the upper slope, between 3990 m and 3670 m water depth. Facies 1 to 2 vertical associations show obvious thickening-upward sequences between depth intervals 4260-4230 m, 3890-3870 m, 3860-3840 m and 3740-3730 m. Most of the samples from this area consist of bioturbated siltstones with lenticular to wavy and flaser bedding; the remnants are fine-grained sandstones.

The thickening and coarsening upward cycles, about 20–40 m thick, are characterized by a thick basal mud-silt member (Facies 1) progressively grading up into an intermediate silt-dominated member (Facies 2) (Fig. 10). We interpret such a basic sequence as a result of progradation of mouth-bar deposits (lenticular to wavy-bedded bioturbated siltstones and thin sandstones) onto thick black clayey-silty formations suggestive of prodelta deposits (Guiraud *et al.*, 1997a). Locally, the upperlying siltstone beds may be truncated by 10 to 30 m, upward thinning and fining, sequences where diffuse lag conglomerates and coarse, large-scale cross-bedding

Plate I

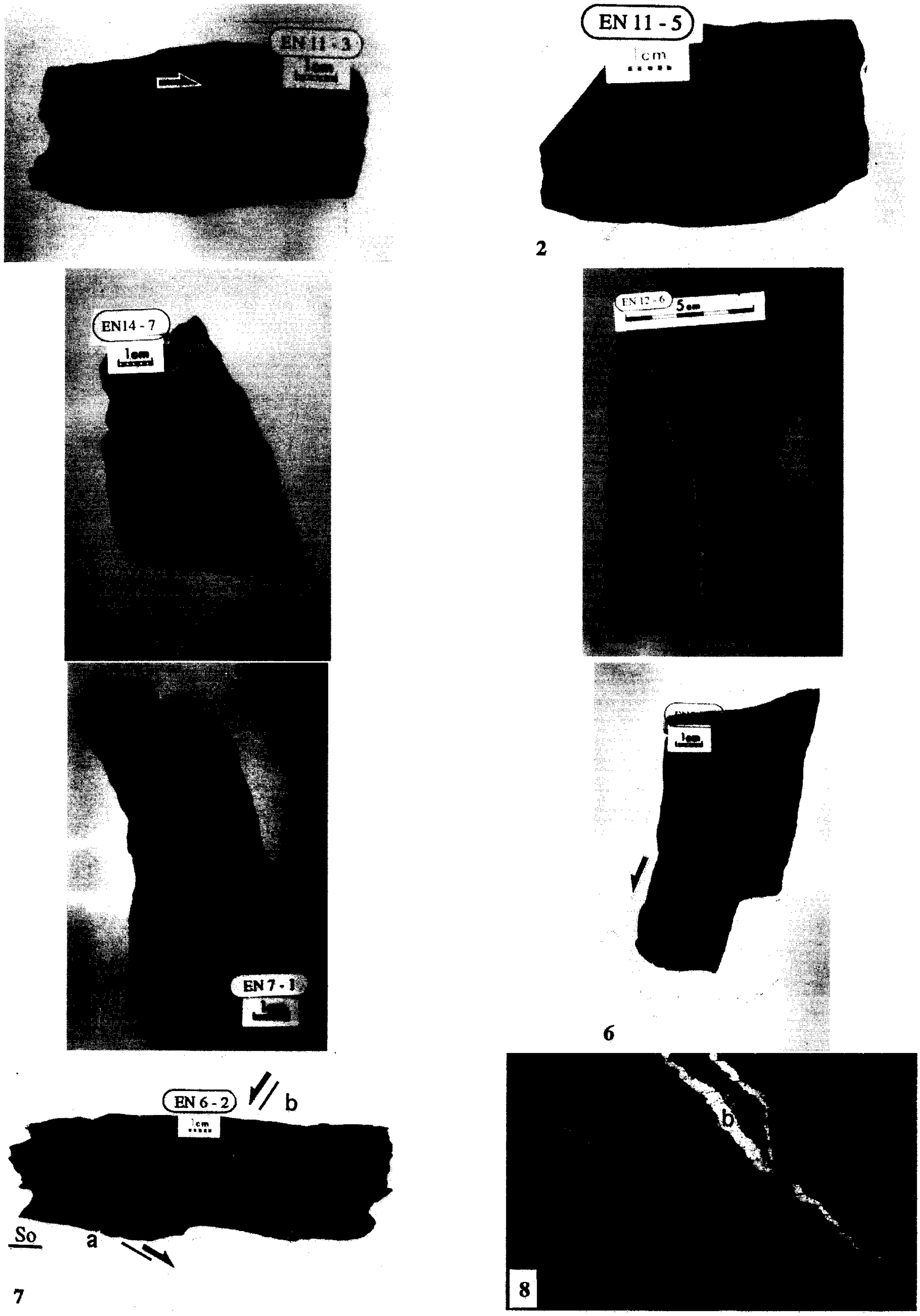
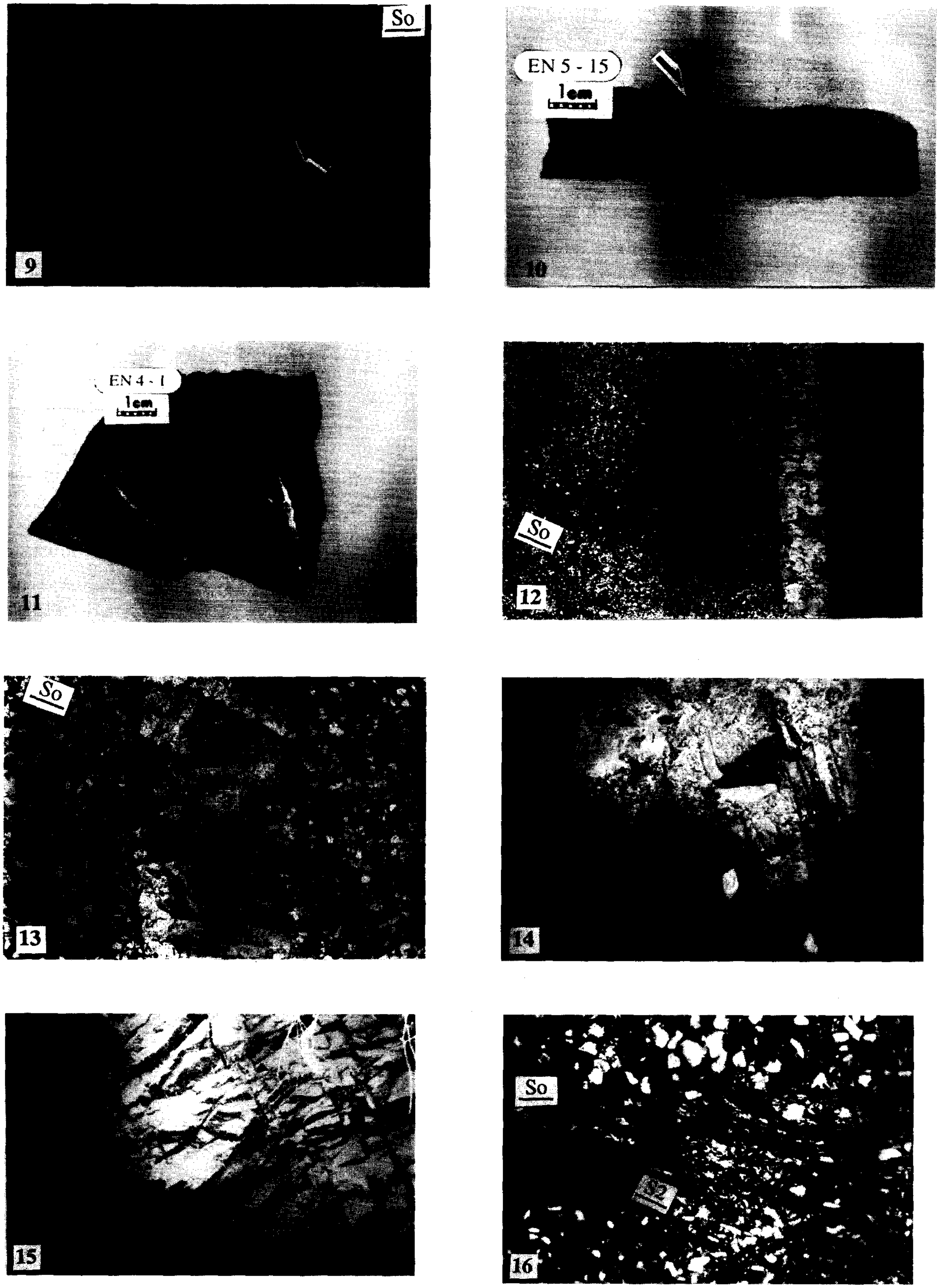

EN 11 - 3
1cm
EN 11 - 5
1cm
2
EN14 - 7
1cm
EN 12 - 6
5cm
EN 7 - 1
1cm
6
EN 6 - 2
1cm
b
So
a
7
b
8

Plate II



sandstones (Facies 3) are prevailing. These pass upward into Facies 4 sandstones, then siltstones and claystones. This second basic sequence, prevailing along the eastern CIGMR (dives EN01 to EN03), is interpreted as result of fluvial distributary channel activity and abandonment. The overlying claystones, rich in plant remains (Facies 4), may themselves be related to a flood-plain environment. Those cycles are believed to represent basic sedimentary sequences, deposited as a consequence of subsidence and sea-level fluctuations and/or a combination of both processes. The lithological sections reconstructed from the eight analysed dives characterize facies associations at the margin scale (Fig. 9).

The deepest dive (EN11), made at the slope foot below 4700 m near the eastern end of the ridge may have documented parts if the CIGMR basement. During this dive, black slaty shales and fine quartzites were sampled; they can tentatively be compared to Early Voltaian metasediments exposed along the Ghanaian coasts (Affaton *et al.*, 1980). Above this potential basement, the overall sedimentary trend corresponds to a progressive upward transition from prodelta distal clays to more proximal facies such as mouth-bar deposits, distributary fluvial sandstones and flood-plain deposits. This trend, observed at a 50 m scale, also exists at the scale of the 2000 m thick sedimentary pile, where distal facies prevail at the base and are progressively replaced upward by more proximal facies. This succession implies a rather constant subsidence through time, which maintained a shallow water depth despite the deposition of more than 2000 m of sediments.

Horizontal correlations between dives remain hypothetical due to both the cyclic nature of the sedimentary log and the distance between each dive. For this attempt, each dive has been divided into several sections in which one of the different sedimentary facies (1 to 4) is prevailing. Accordingly, the correlations suggest that the central and northeastern CIGMR domains (Fig. 9) are tilted slightly northeastward. This may be the result of either syn-sedimentary or post-sedimentary movement of the entire ridge, or alternatively of differential subsidence, possibly triggered by transverse faulting. Within the southwestern ridge corner, dives EN13 and EN14 exhibit mainly Facies 4 sediments (flood-plain deposits), at depths greater than that observed during the dive EN12 (Fig. 12). Such a downward shift is likely to be due to normal faulting, as well evidenced nearby on seismic data (Fig. 7*c*) (Sage, 1994; Lamarche *et al.*, 1997; Basile *et al.*, 1996).

CIGMR DEFORMATIONAL RECORDS

Three successive deformation events are recorded within the indurated clastics exposed along the southern CIGMR slope. They relate respectively to pre-lithification and syn- to post-lithification extensional events and to a post-lithification (chiefly wrenching) stage. Our structural analysises has been conducted combining outcrop descriptions (from *in situ*, video observations and colour photographs), in situ measurements of bedding attitude, fault trends, brittle joints and fold axes, together with microstructure analyses performed on polished hand-sized samples and thin sections (Guiraud *et al.*, 1997*b*); Benkhelil *et al.*, 1997)

Pre-lithification microstructures

Slumping

Claystones exhibit a wide range of disharmonic and isoclinal microfolds (Plate I-1), including isolated re-cumbent microfolds with curvilinear hinges (1 on Fig. 11A; Plate I-2). Sharp thickening, thinning and boudinage of layers suggest ductile deformation mechanisms likely operative in unlithified and water-rich sediments. A few flat-lying microfolds show late, well-expressed and parallel to bedding mineral fabrics (Guiraud *et al.*, 1997*b*). This demonstrates that compaction affected already slumped sediments.

Microfaulting

Slump microfolds are cross-cut by sliding bedding planes. Slickensided microfault planes are often glossy and show a typical metallic glint; they suggest hydroplastic microfaulting occurring in soft sediment (Guiraud and Seguret, 1987). All these features are specified as good evidence of pre-lithification and liquefaction-triggered microstructures, and are believed to reflect gravity-induced submarine slumps within soft clays. They may possibly have been caused by seismic activity.

Pre-lithification deformations are also recorded by listric normal microfaults that dip some 30° to bedding and root into bedding planes (2 on Fig. 11A; Plate I-3). On thin sections, these features are only expressed by diffuse, 0.5 mm thick, zones showing particle redistributions. They may grade upwards into broken-up, chaotic entirely liquefied silty and clayey sediment. According to Ringrose (1988), similar liquefaction-induced microstructures may also be due to earthquake-triggered remobilization of water-rich sediments.

Loadcasts and hydroschistosity (S_l)

Finally, fine-grained sandstone and siltstone beds show frequent loadcasts and associated flames. The related mud pipes (3 on Fig. 11A), almost orthogonal to bedding, which were presumably acting as early dewatering pathways, exhibit a typical fan-shaped "hydroschistosity" pattern (S1 on Fig. 11A) (Benkhelil *et al.*, 1997). In finely laminated siltstones, pencil-like parting fragments are frequently seen on outcrops. This specific pattern reflects a penetrative structure typical of a fracture cleavage. At a microscopic scale the siltstones show cleavage planes, best displayed in clay laminae, and passing to closely-spaced parallel fracture planes in sandy beds. Typical refractions are observed at interfaces between different grain-size lithologies; characteristic "horse tail" type figures, with iron-coated cleavage planes, develop at boundaries between sandstones and claystones.

All those soft sediment microstructures indicate a non-stable depositional environment where gravitational detachments and/or sedimentary remobilizations were probably triggered by seismic shocks.

Syn-lithification extension

Veining

Among the extensional microstructures, two main sets of veins have been distinguished from their respective contacts and infilling, and their relative timing of emplacement (Guiraud *et al.*, 1997*b*).

A first set of tensile quartz veins shows very indented contacts (1 on Fig. 11B; Plate I-4). On thin sections, the veins exhibit suture-like borders that closely follow, but do not truncate, the detrital quartz grains. Moreover, the vein infilling contains euhedral radial quartz and a few angular detrital grains, which are probable sediment remains mixed together with vein fluids during generation. The veins vary in attitude with sediment type. In claystones and siltstones, they appear as conjugated sets of potential normal fractures, together with associated *en echelon* quartz-filled veins; in sandstones the veins are generally normal to bedding. We believe that these first-generation veins originated from grain-to-grain separation mechanisms when the sedimentary matrix was weaker than the framework grains, *i.e.* during lithification. A few normal microfaults are associated with this veining (2 on Fig. 11B; Plate I-5 to 8 and Plate II-9 and 10). They are steep dipping (50-60°) with respect to the layering, and show offsets one millimetre to one centimetre in size. All these features substantiate a probable extension parallel to bedding when bedding was sub-horizontal. Moreover, in two *in situ* oriented samples (EN06-2, EN07-1), the faults, as well as the vein strike parallel to the north-south regional extensional faulting detected northwards within the rifted Ivorian Basin (Figs. 6, 7*a*) (Basile *et al.*, 1993).

Post-lithification deformations

During most of the Equanaute dives, spectacular vertical cliffs of massive sandstones and siltstones (several tens of metres in elevation) were observed (Mascle *et al.*, 1994). An intense fracturing, which resulted in very dense and regular brittle joint systems, has locally, chiefly in siltstones, created typical blocky outcrops. Both intense fracturing and jointing are in our opinion best explained by the effects of wrench-type tectonics, also well recorded, at minor scale by a set of cleavages and mineral recrystallizations (Benkhelil *et al.*, 1997). However, evidence of large-scale normal faulting and the occurrence of a second vein generation also indicate a post-diagenesis extensional activity.

Veining

A second generation set of extensional veins is filled with calcite or quartz crystals orthogonal to tension-gash walls in sharp contacts with the host rock (3 on Fig. 11B; Plate II-11 to 13). The sharp contacts, and the lack of inclusion, as well as the fibrous texture of this late veins strongly suggest that the material was quite cohesive during fracturation, *i.e.* that deformation occurred after lithification. Most of these late veins, appear normal to bedding. However, the sediments may be cut by branch curving veins, particularly in calcite-cemented sandstones. Associated stylolitic joints may occur along bedding planes. In this case, the stylolitic columns appear normal to sedimentary layering. This veining relates to extension parallel to bedding and has recorded both successive microcrack opening and subsequent instantaneous sealing (Ramsay, 1980).

Brittle fracturing and faulting

Brittle fracturing is the most conspicuous record of the post-lithification deformations observed during dives (Benkhelil *et al.*, 1997). It is particularly striking in fine-grained sandstones and siltstones, where it results in specific and regular patterns such as geometrically-cut planar slabs and/or cubic paving stones (Plate I). Brittle joints are well expressed (1 on Fig. 11C; Plate II-14): they locally form series of dense and narrow cleft sets where outcrops appear almost entirely crushed. Usually the joint average dip is quite steep and often sub-orthogonal to bedding; the joints appear preferentially distributed according to N10° E, N45° E, N100° E and N145° E trends.

During dives EN06 and EN07, the observation of planar and crust-coated surfaces a few square metres wide strongly suggests fault scarp planes; sudden dip variations, as well as local increase of fracturing and brittle joints are also suggestive of nearby fault corridors. Brittle faulting is also evidenced at sample scale by sets of normal micro faults, particularly well expressed in fine-grained sandstones and siltstones, where they appear as glossy and slickensided planes. Technical restrictions (narrow view field from the submersible) prevented direct *in situ* observation of large-scale faults; these are, however, strongly suggested by local deep cuts and sharp cliffs seen within massive outcrops. Most of these features are believed to reflect extensional faulting, as also supported by seismic profiling.

Folding

Most of the dives allowed observation of frequent bed dip variations, indicative either of faulting or folding (Fig. 12). Direct evidence of folds was, however, virtually prevented by an *in situ* limited view field. Most of the folds have thus been deduced from careful dip measurements and bedding pole computations on stereonet projections. For example, two upright folds have been reconstructed, upslope between 3100 m and 3000 m, near dive EN03 end (Bouillin, in Mascle *et al.*, 1994) (Fig. 12*a*). Both folds, about 50 m in spacing, correspond to narrow, symmetric anticlines showing an axial fracture cleavage. Interestingly, a second investigation, made some 300 m west of the previous *Nautile* track, indicates a comparable folded structure. Similarly, dives EN05, EN06 and EN13 permitted observation of a series of narrow folds trending N-S to N10° E and N 110° E (Guiraud, in Mascle *et al.*, 1994). Dives EN02, EN07, EN08 and EN12 also exhibit clear folding evidence, preferentially concentrated upslope (Plate II-15). Small-scale folding has, from place to place, been observed. The best example of *in situ* observed folding has been provided by dive EN05, at a water depth of 3165 m. There, a small fold, some metres in length and about one metre high, progressively vanishing upsection, shows a north-east dipping axis; it is interpreted as a probable drag fold generated in a strike-slip regime (Benkhelil *et al.*, 1997).

Folding may also be expressed by very gentle, small-scale folds well recorded within thinly layered sandstones. This has often induced bedding-parallel slips now imprinted on sample bed planes as slikensides.

Most of the folded stuctures trend within north-south to north-east directions, and are seen to concentrate in the upper slope domain (Mascle *et al.*, 1993). Such an observation is in good agreement with the occurrence of drag folds and the apparent concentration of wrench faulting features across the ridge top and bordering the upper slope, as evidenced on seismic reflection data (Basile *et al.*, 1993; Basile *et al.*, 1997).

Cleavages (S_2)

The dominant cleavage S_2 is recorded either as discontinuous plane sets or as narrow compact strips (Plate II-16). The cleavage planes bear syngenetic mica flakes, and evidence of displacement is attested by detrital grain dragging. This cleavage is believed to reflect a shear component during the deformation process (Benkhelil *et al.*, 1997). The S_2 cleavage, detected along most of the entire continental slope segment, intersects an earlier, poorly imprinted cleavage (S_1). On thin sections, braided, almond-like figures have been observed resulting from the intersection, at low angle, of the two S_1 and S_2 cleavages planes, while high angle intersections are emphasized by recrystallized mica flakes. Cleavage attitude measurements made *in situ*, and performed on a few oriented samples, are coherent and indicate an average direction close to N 50° E, identical to the fold axis mean direction (see above); this strongly suggests a common origin.

Low-grade thermal transformations

The general greenish color of most of the retrieved samples testifies, at first, that low-grade thermal metamorphism has been once operative within the sedimentary section (Benkhelil *et al.*, 1997). Clayey and silty formations have best recorded the mineral imprints of such thermal events attested, on thin sections, by microflakes of illite, chlorite and biotite, all being recrystallized along cleavage planes. An early similar mineral assemblage is present in the sediments, but is intersected by S_2 cleavage.

Chloritic stacks, including, here and there, interlayered muscovite flakes, are occasionally seen in claystone and siltstone samples. These stacks, rarely observed in sandstones, are known to be indicative of very low-grade transformations (Craig *et al.*, 1982). A similar early thermal event has been documented, further east of the studied area, in the lower Benue trough (Nigeria), which was characterized, at the same time span, by a rather comparable sedimentary and tectonic evolution (Benkhelil, 1988).

DISCUSSION

From the seismic reflection data set recorded prior to scientific dives, and according to experimental modelling of the deformations at the rift-transform intersection, Basile *et al.* (1992, 1993) have proposed a four-stage tectonic evolution of the Côte d'Ivoire-Ghana Transform Margin. This tectonic model, which may account for other transform margin segments, includes: rifting, continental transform, continent-ocean transform and, finally, passive margin stages.

RIFTING. According to available seismic data (seismic stratigraphy and structure; see above) during an early extensional stage, the continental crust of the future Deep Ivorian Basin started to stretch as a consequence of rifting between Equatorial West Africa and northeast Brazil, in early Cretaceous times. This resulted in the creation of a series of north-south half-grabens and associated rotated blocks such as those illustrated on Figure 7*a*. The coeval synrift unit was deposited with thickness in excess of 3 km in some grabens over the whole thinning basin, including along its southern border (the future CIGMR domain), where tilted horsts and accompanying half grabens were also generated (Fig. 7*c*).

Equanaute dive observations and geological samples demonstrate that the sedimentation was then terrigenous in the future CIGMR domain. The steep CIGMR southern slope effectively corresponds to a clastic succession, at least 2200 m thick, in which three major lithofacies are identified: (a) dark, organic-matter rich claystones; (b) laminated siltstones, and interbedded fine-grained sandstones; (c) grey coarse sandstones and microconglomerates. These sediments were in all likelihood accumulated within a shallow marine environment of deltaic type, sometimes submitted to open marine influence. Some of them were even deposited in a probable sub-aerial setting, as evidenced by the recovery of thinly-laminated sediments attributed to lake deposits and scarce indications of sub-aerial exposures. Along the future transform ridge, the shallow detrital sedimentation, dating from early Cretaceous time (at least Albian), was probably directly influenced by the vicinity of the Brazilian continental shelf, as attested by its dominantly shallow depositional environment characteristics and the occurrence of thick progradational wedges detected on multichannel seismic data across the eastern CIGMR (Lamarche *et al.*, 1997). Microstructural analysis of the samples also clearly substantiates that the clastics were deposited on a tectonically unstable platform submitted to rapid subsidence, gravity-induced slumping and faulting, and probable earthquake shocks. These conclusions are supported by an overall sediment thickness in excess of 3 km (according to refraction data), pre-lithification microfolds, hydroplastic shear fractures and other liquefaction-induced microstructures. Syn-lithification extensional microstructures (quartz veins and normal microfaults) may indicate incipient strike-slip related deformations, inferred as initiating along the southern Deep Ivorian Basin, *i.e.* within the future CIGMR domain, before the end of rifting. Their apparent north-south strike, similar to the general trend of the divergent basin extensional blocks, suggests, however, that extension persisted during sedimentary lithification.

CONTINENTAL TRANSFORM. Rifting ceased in the Deep Ivorian Basin when the oceanic crust was created along its western edge. Continental break-up was then recorded in the area by a typical post-rift unconformity and by the deposition of seismic unit B in wide asymmetric depocentres (Fig. 7*a*). Along the CIGMR domain, initiation of the drift stage induced wrench tectonics as a consequence of transform-type motion between the two parting continental plates. This stage also induced an increasing wrench deformation on the CIGMR itself. In the central and western CIGMR (the upper clastic section), locally truncated by conglomerates and cross-bedding sandstones may constitute a sedimentary record of this event. Isopach folding and related bedding-parallel slips (chiefly recorded within homogeneous shaly, silty or interbedded siltstone-sandstone formations), coeval slight flattening deformation (well attested by cleavage), and finally the dense fracturing (which has resulted in a remarkable slope shaping), are interpreted as tectonic identifications of such intracontinental wrenching activity. Moreover, dive observations clearly attest that deformations are increasing upslope. This observation is consistent with seismic reflection data which illustrate drag folds and branching wrench-related lineaments over the ridge top and adjacent sedimentary basin (Basile *et al.*, 1993).

CONTINENTAL OCEAN TRANSFORM. Final continental parting between west Africa and northeast Brazil is believed to have occurred in the area around Santonian times (Mascle *et al.*, 1988; Basile *et al.*, 1993). This event resulted in the establishment of tectonically active contacts between the newly created Gulf of Guinea oceanic crust and the continental CIGMR transform fault, that became, at this time, an active continental transform margin segment. The active transform system is thought to have then shifted toward the thin, and weaker, oceanic crust whose stucture is apparently made of thin uppermantle-derived serpentinites and gabbroic bodies (Sage *et al.*, 1997).

Starting from this time period, differences in depth between a thick continental border and the oceanic basin are anticipated to have led to gravitational sliding toward the south, and finally, to the creation of the CIGMR southern slope, as well to subsequent uncovering and erosion of early Cretaceous clastic sediments. A cooling episode, evidenced in late Cretaceous times by fission track analysis on Equanaute samples, indicates an age for passing the 60 °C isotherm progressively younger downslope and toward the west. Such timing appears in good agreement with a progressive slope uncovering itself following progressive oceanic crust creation moving toward the west. Major faulting along the southern ridge slope should be expected from such a general collapse. The few fault scarps and the spectacular rock chaos observed at the base of the CIGMR central domain slope may be the records of this event.

Finally, during this time interval, the sharp contact, on the order of 5–10 km (Sage, 1994) established between the hot oceanic lithosphere and a colder continental crust should have also induced strong thermal gradients and resulted in subsequent CIGMR thermal uplift (Todd and Keen, 1989; Lorenzo and Vera, 1992). Within the Deep Ivorian Basin, coeval sedimentation and depositional arrangements have apparently recorded such an uplift, while the previous sedimentary units were tilted northward. This thermal-triggered uplift probably increased until the passage of the oceanic spreading ridge (Basile *et al.*, 1993).

PASSIVE MARGIN STAGES. Active tectonism along the transform margin ceased when the spreading centre passed south of the Côte d'Ivoire-Ghana Margin. The transform margin and the adjacent oceanic basin then began to subside as far as the present sea floor depth (2010 m for the ridge top) as a result of thermal subsidence. Subsequently, the strong structural damming effect of the CIGMR prevented most of the African detrital sediment input to bypass from the Deep Ivorian Basin.

CONCLUSIONS

Observations and geological samples collected during the Equanaute deep dives across the Cote-d'Ivoire-Ghana Marginal Ridge southern slope provide constraints about the lithology, the depositional environment, and partly the age of the thick sedimentary pile which constitutes most of the ridge. The data also provide support for the tectonic and thermal regimes that controlled the transform ridge fabric and edification. The CIGMR southern slope consists of a deformed wedge of dominantly shallow clastics, likely to have been deposited in Early Cretaceous time. The present-day feature results from a relatively complex tectonic and subsidence story. The major stages of the transform ridge evolution, deduced from integration of geological (deep dive results) and geophysical data (chiefly seismic reflection) are as follows:

(1) A period of divergent rifting (Early Cretaceous, probably Barremian to late Aptian), characterized by dominant shallow clastic deposition on an unstable platform cut in a series of rotated blocks and rapidly subsiding half-grabens. Concurrently, or soon after, the CIGMR initiated as a structural relief in response to active wrench tectonics at the boundaries between two sliding continental masses (western Equatorial Africa and northeastern Brazil).

(2) This resulted in a second deformational episode, recorded on the ridge top and across the southern ridge slope in an intense and striking fracturing and, chiefly upslope, in a series of drag folds, and wrench-related lineaments best explained by a general N 60 ° E right-lateral motion.

(3) Subsequent and progressive contact through time with an adjacent oceanic crust leads: (a) to a non-documented but probable southward shift of the main shear zone within an incipient Romanche oceanic/continental transform; (b)

to a new, thermally triggered, CIGMR uplift attested by a strong erosional surface and by drastic changes in coeval depositional arrangements; (c) to a probable general gravitational collapse of the CIGMR southern slope as documented by progressive westward uncovering of the clastic units, now directly exposed along the slope.

(4) In a final stage, whose initial timing remains to be checked, the CIGMR began to subside by normal cooling, as expected for a passive margin segment.

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