



HAL
open science

Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history

G. Péron-Pinvidic, G. Manatschal, T.A. Minshull, D.S. Sawyer

► **To cite this version:**

G. Péron-Pinvidic, G. Manatschal, T.A. Minshull, D.S. Sawyer. Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history. *Tectonics*, 2007, 26 (2), pp.TC2011. 10.1029/2006TC001970 . hal-00178575

HAL Id: hal-00178575

<https://hal.science/hal-00178575>

Submitted on 2 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history

Gwenn Péron-Pinvidic,¹ Gianreto Manatschal,¹ Tim A. Minshull,² and Dale S. Sawyer³

Received 16 March 2006; revised 18 December 2006; accepted 17 January 2007; published 6 April 2007.

[1] Most of the conceptual ideas concerning sedimentary architecture and tectonic evolution of deep rifted margins are based on either intracontinental rift basins or proximal margins, both of which underwent only small amounts of crustal thinning. In this paper, we investigate the tectonosedimentary and morphotectonic evolution related to continental breakup of the highly extended, deep Iberia-Newfoundland margins. Our results show that continental breakup is a complex process distributed in time and space. On the basis of mapping of dated seismic units and borehole data we are able to identify two major phases of extension. During a first phase, dated as Tithonian to Barremian (145–128 Ma), deformation is related to exhumation of mantle rocks; basins become younger oceanward, and fault geometry changes from upward to downward concave resulting in complex sedimentary structures and basin geometries. A second phase, dated as latest Aptian (112 Ma), overprints previously exhumed mantle and accreted juvenile oceanic crust over more than 200 km leading to the formation of basement highs. The observed complex breakup history challenges classical concepts of rifting and leads to new interpretations for the tectonosedimentary evolution of deep rifted margins. **Citation:** Péron-Pinvidic, G., G. Manatschal, T. A. Minshull, and D. S. Sawyer (2007), Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history, *Tectonics*, 26, TC2011, doi:10.1029/2006TC001970.

1. Introduction

[2] In classical models of rifted margins the juxtaposition of continental and oceanic crust was represented as a sharp well defined boundary, and the thinning of the continental crust was explained by simple or pure shear mechanisms, or a combination of the two [McKenzie, 1978; Wernicke, 1985; Lister *et al.*, 1986; Boillot *et al.*, 1987]. Implicit in these models was the idea that seafloor

spreading directly follows rifting and that continental breakup is a process that is well defined in time and space and recorded in the sedimentary sequence by tectonic and thermal subsidence and a breakup unconformity [Driscoll *et al.*, 1995]. However, drilling in the deep Iberia and Newfoundland margins (Ocean Drilling Program (ODP) legs 103, 149, 173 and 210 [Boillot *et al.*, 1987; Sawyer *et al.*, 1994; Whitmarsh *et al.*, 1998; Shipboard Scientific Party, 2004]) combined with the acquisition of high-quality geophysical data cast doubt on this classical view. The simple juxtaposition of continental and oceanic crust with a well defined continent-ocean boundary was replaced by a zone of exhumed continental mantle (ZECM [Whitmarsh *et al.*, 2001]), often also referred to as an ocean-continent transition (OCT). This zone off Iberia, formed by tectonically exhumed mantle, is up to 170 km wide and exhibits specific geophysical characteristics that are neither continental nor oceanic. Its key characteristics are weak and nonlinear magnetic anomalies, pronounced basement topography, a particular seismic velocity structure with strong gradients and a lack of a clear Moho reflection. The new observations challenged the value of simple models and their validity in unraveling the tectonic evolution of deep magma-poor margins. On the basis of a review of the present-day west Iberia margin and exposed remnants of an ancient OCT in the Alps, Whitmarsh *et al.* [2001] and Manatschal [2004] proposed and further developed a conceptual tectonic model for the evolution of magma-poor margins that has been also modeled numerically [Lavie and Manatschal, 2006]. This model consists of a polyphase evolution of rifting with three major modes of extension: a stretching mode, a thinning mode, and an exhumation mode. Although the numerical model is able to reproduce the sequence of deformation phases observed at the Iberia and Alpine Tethys margins, the tectonosedimentary evolution associated with these deformation phases is still poorly understood.

[3] The aim of this paper is to examine how the complex sequence of deformation phases related to continental breakup is recorded in the sedimentary architecture. In order to answer to this question, we mapped the three-dimensional (3-D) architecture of dated sedimentary units in the Southern Iberia Abyssal Plain (SIAP) and used drilling results from ODP legs 149, 173 and 210 from the conjugate Iberia and Newfoundland margins. Our results show that the sedimentary architecture in the OCT records a complex tectonosedimentary and morphotectonic evolution that sup-

¹Institut de Physique du Globe de Strasbourg/Centre de Géochimie de la Surface, Ecole et Observatoire des Sciences de la Terre, Strasbourg, France.

²School of Ocean and Earth Science, National Oceanography Centre, Southampton, UK.

³Department of Earth Science, Rice University, Houston, Texas, USA.

ports the idea that continental breakup in magma-poor margins is distributed in time and space.

2. Tectonosedimentary Evolution of the Iberia-Newfoundland Conjugate Margins

2.1. Structural Evolution

[4] The West Iberia and Newfoundland margins are conjugate, passive magma-poor margins that resulted from the Late Triassic to Early Cretaceous rifting and separation of the North America/Flemish Cap and Europe/Iberia plates. The detailed plate kinematics, the age of distinct rift episodes and final breakup, and the importance of inherited Variscan structures on the final architecture of this pair of margins are still debated. According to the most recent paleogeographical reconstructions of *Srivastava et al.* [2000] and *Sibuet et al.* [2007], the correspondence between conjugate sections is obscured by the complex relationship between the Iberia and Flemish Cap microplates. Because neither the age of separation nor the amount of rotation of the two plates before separation is established, a precise reconstruction of the Iberia-Newfoundland conjugate margins is not yet possible. However, the M0 regional reconstruction of *Srivastava et al.* [2000] is widely accepted. It supposes that the southeastern border of Flemish Cap represents the conjugate of the northern West Iberia margin.

[5] Concerning the tectonic evolution of the margin, *Tucholke et al.* [2007] distinguished two major rift phases: an older Late Triassic phase and a younger Late Jurassic to Early Cretaceous phase. During the earlier phase, large and deep fault-bounded rift basins formed in the proximal margins (e.g., Jeanne d'Arc, Lusitanian and Galicia Interior) (Figure 1a). These classical rift basins were produced in a pure shear environment (e.g., stretching phase of *Lavier and Manatschal* [2006]). During later Oxfordian to Kimmeridgian and Valanginian to Hauterivian rifting, extension migrated from more proximal to more distal parts of the future margin. During this extension, the crust was first thinned to less than 10 km before subcontinental mantle was exhumed along downward concave faults to the seafloor (e.g., thinning and exhumation phases of *Lavier and Manatschal* [2006]). The age of final breakup in the SIAP is still debated. On the basis of the first oceanic magnetic anomaly M3, *Whitmarsh and Miles* [1995] and *Russell and Whitmarsh* [2003] suggested a Barremian age (128 Ma), *Wilson et al.* [2001] suggested a Valanginian age (140–134 Ma), whereas on the basis of stratigraphic arguments, *Tucholke et al.* [2007] proposed a late Aptian age (112 Ma) (timescale used in this paper [*Gradstein and Ogg*, 2004]).

[6] A key observation for the evolution of rifting along the Iberia-Newfoundland margins is the progressive localization of rifting into the area of the future breakup as well as its propagation from south toward the north. This overall trend can be observed on the scale of the whole Iberia-Newfoundland rift system [*Srivastava et al.*,

1988; *Boillot et al.*, 1989; *Murillas et al.*, 1990] but also, as shown in this paper, on the scale of the SIAP. The migration and localization of deformation toward more distal parts of the margin that is associated with a change in the mode of extension can explain the very different structural evolution of proximal and distal margins (Figure 1b).

2.2. Drilling Results

[7] The Iberia-Newfoundland conjugate margins are at present the only pair of deep magma-poor margins where deep sea drilling has sampled basement on both margins. The 18 sites drilled during DSDP Leg 47B and ODP legs 103, 149, and 173 [*Sibuet et al.*, 1979; *Boillot et al.*, 1987; *Sawyer et al.*, 1994; *Whitmarsh et al.*, 1998], and the dense geophysical data coverage mean that the Iberia-Newfoundland margins are considered as the type example of a magma-poor rifted margin [*Shipboard Scientific Party*, 2004]. The most spectacular drilling result was the discovery of exhumed mantle on ODP Leg 103 at Site 637 in the Deep Galicia margin [*Boillot et al.*, 1987]. Although the existence of exhumed mantle rocks in distal domains had been proposed previously by *Decandia and Elter* [1972], based on the discovery of clasts of mantle rocks in postrift sediments from the Ligurian Apennines, this result motivated further the study of deep margins. Subsequent drilling campaigns (ODP legs 149 and 173) targeted highs and were designed to drill into basement. This strategy revealed the compositional variation, structure and distribution of mantle rocks in the western Iberia margin and their relationships with the adjacent continental crust. Unfortunately, the transition into clearly identified oceanic crust has not yet been drilled and remains enigmatic.

[8] A very important aspect in the study of rifted margins is the identification of synrift stratigraphic intervals. As discussed by *Wilson et al.* [2001], the determination of synrift sequences in the west Iberia margin is hampered by the lack of data. Only one meter of the critical interval was drilled at Site 1069 (for more details, see *Wilson et al.* [2001, Figure 13]) and in seismic sections clearly syntectonic units are rare and have not been drilled. However, in this paper we present an alternative approach to the classification of synrift stratigraphic intervals to that presented by *Wilson et al.* [2001].

[9] Another important drilling result is the discovery of tectonosedimentary breccias over all basement highs drilled in the Iberia-Newfoundland margins. These breccias are associated with either debris flows, olistostromes, or ophiolites and are locally dated as Aptian [*De Kaenel and Bergen*, 1996; *Whitmarsh and Wallace*, 2001]. While initially their occurrence was interpreted to be related to a local tectonic event [*Comas et al.*, 1996; *Gibson et al.*, 1996], their widespread occurrence over all basement highs in the Iberia-Newfoundland margins suggests that these breccias are related to a more regional event. Although several hypotheses have been put forward to explain this observation [*Whitmarsh and Sawyer*, 1996], these were never

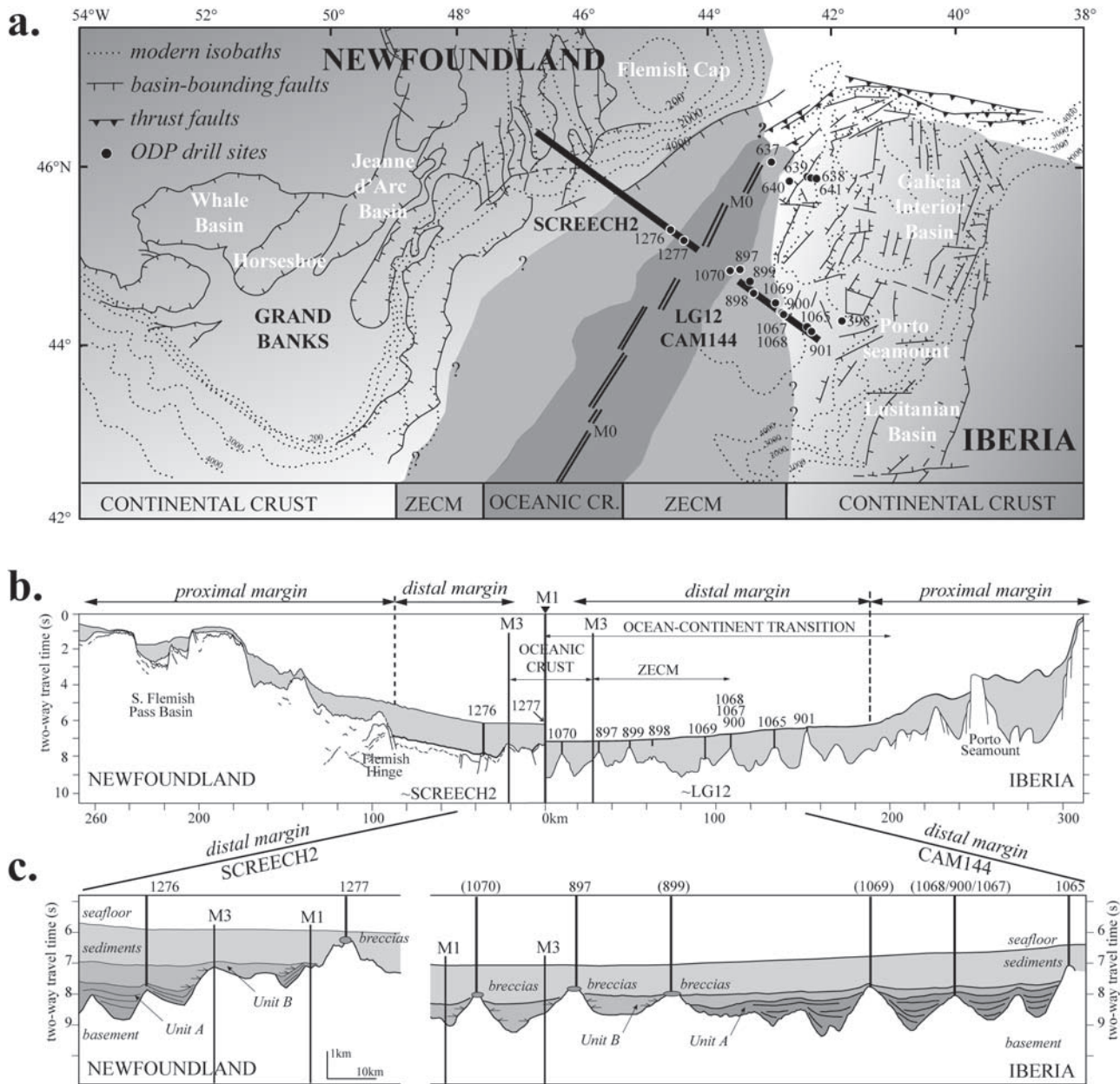


Figure 1. (a) Reconstruction of the Newfoundland-Iberia rifted margins at magnetic anomaly M0 showing the distribution of continental, transitional and oceanic domains [after *Shipboard Scientific Party*, 2004; *Srivastava et al.*, 2000]. Numbers refer to ODP sites. (b) Conjugate seismic sections from the Newfoundland and Iberia margins juxtaposed at magnetic anomaly ~M1 [after *Shipboard Scientific Party*, 2004; *Srivastava et al.*, 2000]. (c) Schematic east-west directed section across the deep Newfoundland and Iberia margins showing the distribution of units A and B. ZECM, zone of exhumed continental mantle. SCREECH2, LG12, CAM144, seismic reflection profiles.

integrated in an overall tectonic model of the margin evolution.

2.3. Seismic Reflection Data Set

[10] The West Iberia margin is traditionally divided into three provinces, easily identifiable on a bathymetric map of

the region (Figures 1 and 2): the Galicia Margin in the north (41°N–43°30'N), or Deep Galicia Margin west of ~12°15'W; the Southern Iberia Abyssal Plain (SIAP) in the center (40°–41°N); and the subcircular basin of Tagus Abyssal Plain in the south. Our work focused on the SIAP. The dense seismic coverage combined with the many

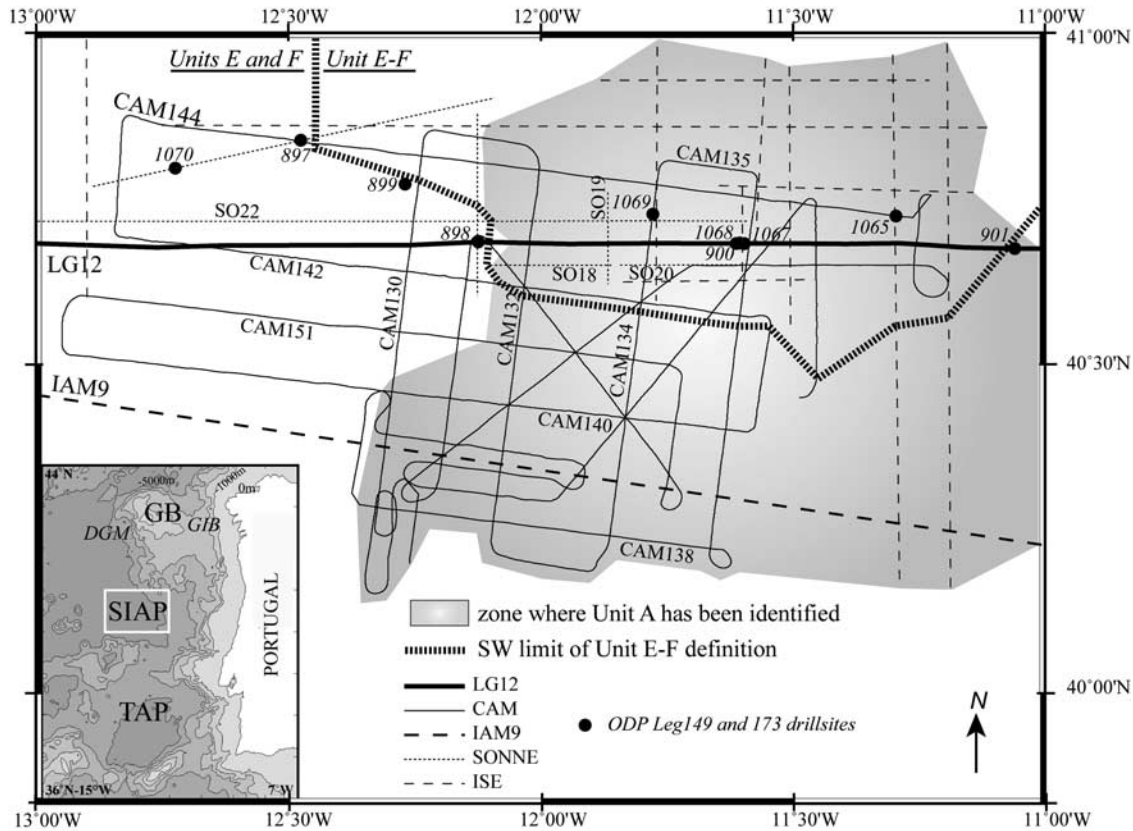


Figure 2. Southern Iberia Abyssal Plain with location of the time-migrated seismic profiles used in the study. Thin lines mark the CAM profiles [Discovery 215 Working Group, 1998]. Different dashed lines mark the Sonne [Roesser et al., 1992], the ISE [Henning et al., 2004], and the IAM9 profiles [Pickup et al., 1996]. A bold line marks the Lusigal12 profile [Groupe Galice, 1979]. Circles represent Ocean Drilling Program legs 149 and 173 boreholes. The inset shows a bathymetric map of the West Iberia margin and the location of the study area (GB, Galicia Bank; SIAP, Southern Iberia Abyssal Plain; TAP, Tagus Abyssal Plain; DGM, Deep Galicia margin; GIB, Galicia Interior Basin). The grayish zone is a schematic representation where unit A has been seismically identified. The thick bold line delimits the eastern domain of the SIAP where composite unit E–F had to be defined since units E and F cannot be mapped separately.

boreholes make the SIAP an ideal place to map and correlate seismic units over a large distance.

[11] The study presented here is based on the analysis of several multichannel seismic time-migrated profiles (Figure 2): LUSIGAL 12 (LG12) [Groupe Galice, 1979; Beslier, 1996]; IAM9 [Pickup et al., 1996]; Sonne [Roesser et al., 1992]; CAM [Discovery 215 Working Group, 1998]; ISE [Henning et al., 2004]; and GP [Mauffret and Montadert, 1987]. The large number of intersecting lines provides good coverage of the margin. Moreover, large subsets (CAM and ISE) have uniform acquisition and processing parameters. This uniformity enables a coherent study of the seismic characteristics throughout the margin and permits a consistent 3-D approach.

3. Sedimentary Architecture

[12] In the SIAP, six seismic sedimentary units (labeled A to F) were defined for the CAM lines, based on our own

observations and on definitions given by Wilson et al. [1996] (Figure 3). Correlations with the lithologies sampled at DSDP Site 398 [Sibuet et al., 1979] and during ODP legs 149 and 173 [Sawyer et al., 1994; Whitmarsh et al., 1998] were made in order to characterize the nature, the depositional environment and the biostratigraphic ages of the intervals (Figure 4) (for details, see Péron-Pinvidic [2006]). Comparisons with previous subdivisions published by Groupe Galice [1979], Mauffret and Montadert [1988] and Tucholke et al. [2007] are presented in Figure 4.

[13] In the following, we subdivide the description of the sedimentary units into a pre-Albian sequence (e.g., unit A) and a post-Aptian sequence (units B to F). This subdivision corresponds to the classical partitioning into synrift and postrift sediments, a subdivision that we believe needs to be used with some reservation, as discussed later in this paper. Moreover, all highs drilled in the OCT of the Iberia-Newfoundland margins (ODP sites 897, 899, 1068, 1070 and 1277) are capped, as previously mentioned, by breccias.

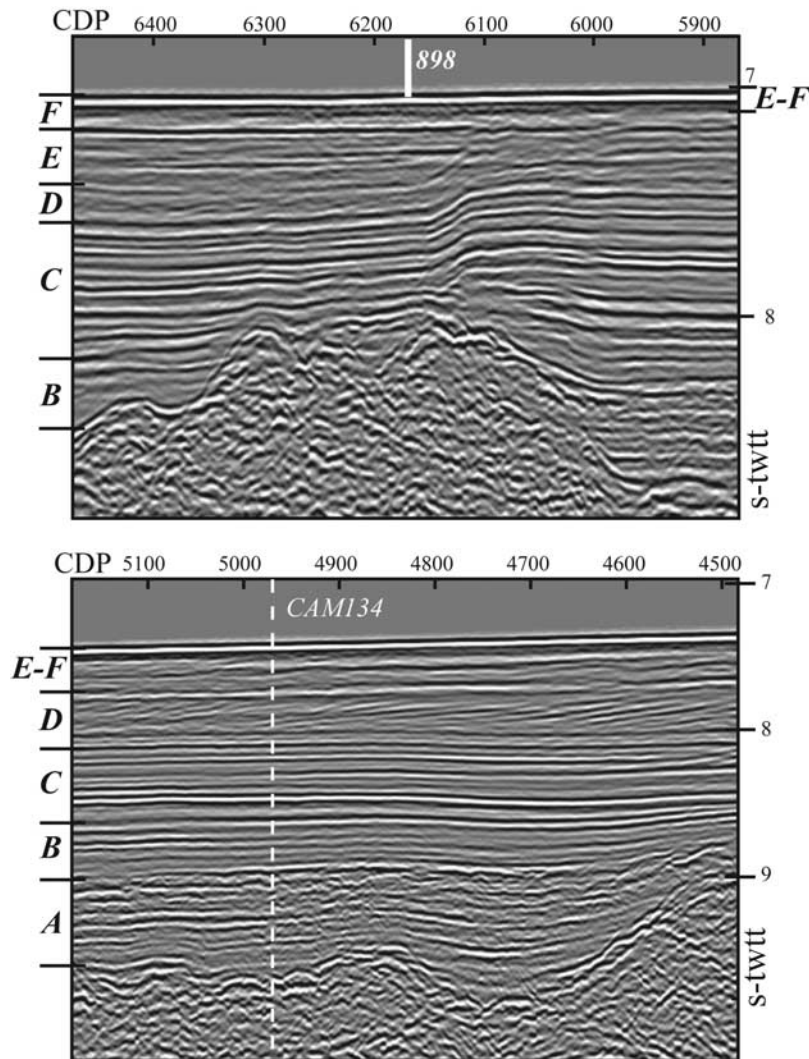


Figure 3. Parts of the time-migrated seismic profile CAM142 showing some of the characteristics of the seismic units. Vertical scale is in seconds of two-way traveltime. Common depth point (CDP) spacing is 12.5 m. The limits between the seismic units are indicated on the left axes. The 898 refers to the position of ODP Site 898.

Because of the importance of these breccias for the later interpretation of the morphotectonic evolution of the margin, we review some of the major observations related to their occurrence and include them in our genetic model of the margin evolution.

3.1. Pre-Albian Sequence (Unit A)

[14] Seismic unit A corresponds over most of the margin to the first identifiable sedimentary sequence overlying acoustic basement. The latter may correspond to either crustal, mantle or magmatic material, potentially covered by prerift sediments in the continental part. The Tithonian sedimentary intervals drilled at ODP sites 901, 1065 and 1069 that are tilted with the underlying continental blocks are therefore defined in this paper as part of acoustic basement.

[15] The upper limit of unit A is marked by a strong and continuous reflector and by the downward change from the acoustic transparency of unit B to the more chaotic character of unit A. The lower limit of the unit is, where detectable, the top-basement reflector. Facies correlations with ODP Leg 210 seismic survey area [*Shipboard Scientific Party*, 2004] and with DSDP Site 398 [*Groupe Galice*, 1979; *Wilson et al.*, 1996] suggest a Valanginian to late Aptian age (140–112 Ma) for this unit (Figure 4). The main lithologies are turbiditic sandstones and siltstones with numerous slumped beds and debris flows interbedded with dark shales.

[16] Stratigraphically, unit A can be subdivided into four subunits labeled, from bottom to top as A1–A4 (Figure 5). The CAM144 profile exhibits a succession of five half-graben-type basins. The basins have been labeled I to V and

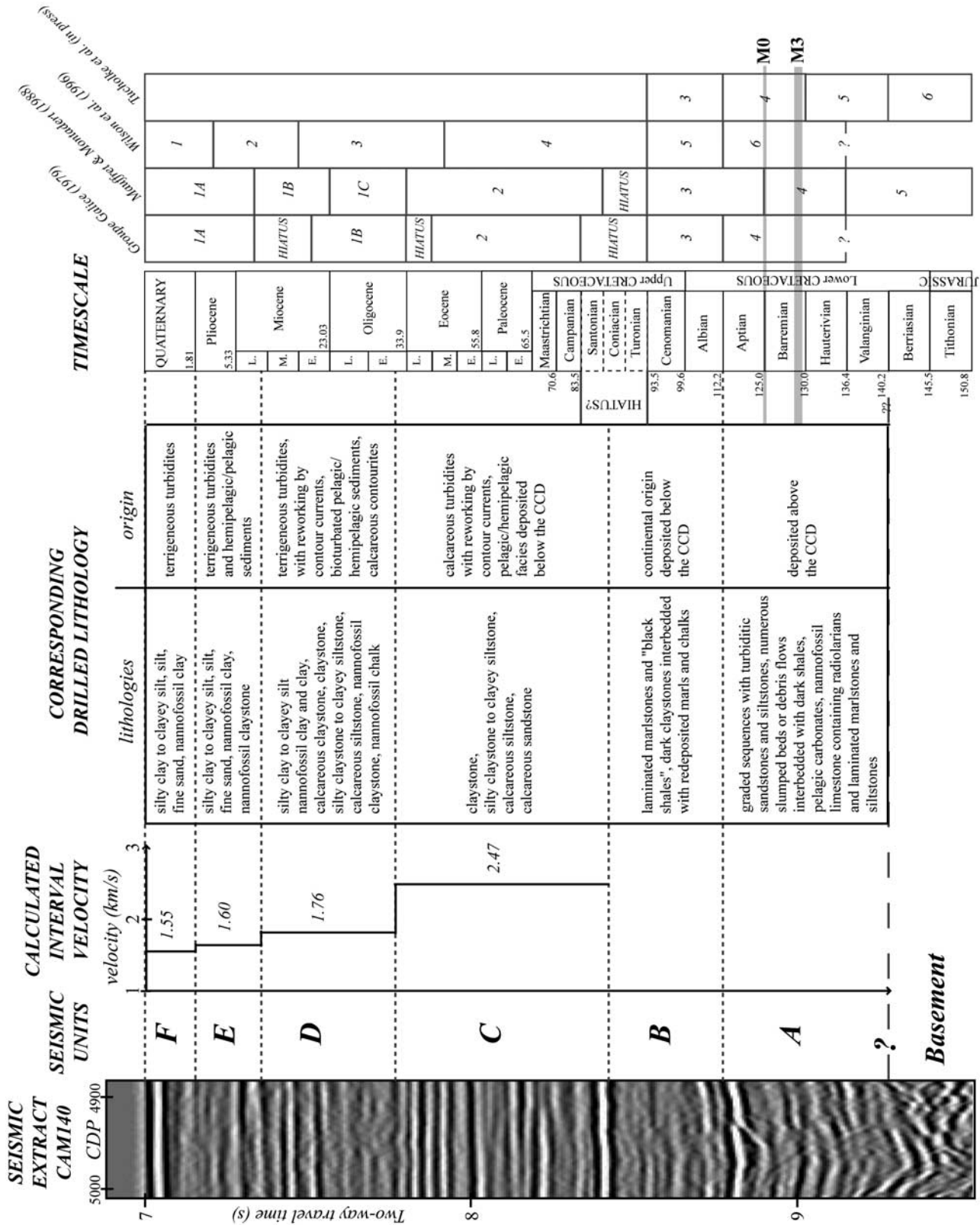


Figure 4

the tilted blocks B1 to B6, from east to west, in order to facilitate the description of sedimentary geometries (Figure 5).

[17] 1. Subunit A1 represents the first sediments that have been deposited onto the acoustic basement. The subunit is chaotic to transparent and few low-amplitude reflections are visible within basins III and IV. These reflections dip toward the east (toward the continent). Only within basins IV and V does subunit A1 show thickening toward the faults.

[18] 2. Subunit A2 is more irregular. Transparent to slightly chaotic within basins I and II, it becomes chaotic with variable amplitude and discontinuous reflections within the western basins. The transition from A2 to A3 is marked by a moderate to high-amplitude reflector with relatively good continuity. The reflections in subunit A2 also dip toward the east in basins III and IV (Figure 5).

[19] 3. Subunit A3 underlies subunit A4, from which it is separated by a continuous reflector with moderate to high amplitude. The subunit has a homogeneous seismic character across the basins with continuous parallel reflections with low to moderate amplitude and horizontal deposition onlapping the underlying subunits.

[20] 4. Subunit A4 has a chaotic seismic character with numerous discontinuous reflections, sometimes diffuse, exhibiting varying amplitudes. The layering is subhorizontal, onlapping the underlying subunit A3 and onto the flanks of the adjacent basement highs. Truncations of A3 by A4 are observed in basin V. The subunit's thickness is variable both within and between the various basins. This variability may be due to the draping of the topography, differences in sedimentary compaction and/or to variable sediment supply.

3.1.1. Syntectonic Growth Structures

[21] Contrary to descriptions by *Wilson et al.* [1996, 2001], we observe in unit A eastward dipping reflection sequences thickening into the footwall of main boundary faults (Figure 5). Such growth structures, classically interpreted to form during syndepositional faulting, can be identified along profiles CAM144, ISE10, and ISE11 (Figure 6). A more detailed analysis of the distribution of growth structures in unit A shows that these are not present in all fault bounded basins (Figure 5). In basins I and II on line CAM144, all subunits have subhorizontal reflections that converge only slightly toward the tilted hanging wall fault block. This convergence may be explained either by a slight tilting, by differential compaction and/or by sedimentary draping. In basins III and IV further oceanward, the reflections belonging to subunits A1 and A2 dip toward the continent. They form wedges thickening into the footwall and are onlapped by the subhorizontal reflections of subunits A3 and A4. In basin IV, subunit A1 forms a wedge that is tilted along a west dipping normal fault. The overlying subunit A2 seals this high-angle normal fault and is tilted itself along the major fault bounding basin IV.

Finally, basin V is less thick. However, subunit A1 looks tilted, although the reflections are less well developed and more difficult to interpret. On the basis of the distribution of growth structures in the SIAP, exemplified by seismic line CAM144, one can see that high-angle normal faults were active before and during deposition of subunits A1 and A2. Mapping of the distribution of the growth structures in the SIAP shows that normal faults become younger oceanward. However, on the scale of a single basin (e.g., basin IV, Figure 5), a more complicated fault evolution can be observed, suggesting the transition from distributed fault activity along several smaller faults to localized displacement along one well-defined major fault [*Chevalier et al.*, 2003; *Cowie et al.*, 2005].

3.1.2. Lateral Variations in Sedimentary Architecture

[22] A change in the fault geometry and associated basin architecture is observed to occur along-strike of blocks B4 to B6 from line CAM144 in the north to line LG12 in the south (Figure 6). Whereas in the north the sediments were deposited in classical fault-bounded basins forming growth structures, in the south they overlie subhorizontally a top basement detachment fault, referred to as the Hobby High Detachment fault (HHD). This HHD has a break away to the east, forms the top of block B4 and cuts at Hobby High (sites 900, 1067 and 1068) from the crust into mantle. Further oceanward, it is overlain by an extensional allochthon (block B5) drilled at Site 1069 (Figure 6; for a more detailed description of the HHD, see *Manatschal et al.* [2001]).

[23] On the basis of mapping of these different basement structures and sedimentary geometries in the dense coverage of seismic profiles in the SIAP, we were able to identify and correlate a number of the structures and reflections along-strike from south to north. This work enables us to propose a 3-D model of the basement structure observed in the SIAP (Figure 6c) and to demonstrate that there is a direct continuity between the structures observed along profiles LG12 and CAM144 (see section 4).

3.2. Post-Aptian Sequence (Units B–F)

[24] The post-Aptian sediments can be subdivided into six seismic units (Figures 3 and 4).

[25] 1. Seismic unit B frequently lies directly on the basement in the western regions where unit A is not resolved in seismic sections. It onlaps topographic highs, almost filling the basins between them. The major characteristic of this unit is its transparency. This transparent layer is very recognizable and hence permits correlation from the SIAP to DSDP Site 398 and to the Newfoundland margin at Leg 210 Site 1276 where it has been drilled. This correlation indicates that unit B corresponds to the Albian-Cenomanian “black shales” representing the first truly post breakup unit (see below). Seismic unit B strongly thickens

Figure 4. Definition of the six seismic units used in this study showing: example seismic data from line CAM140 exemplifying the seismic appearance of the various units; mean velocity values for each unit [*Péron-Pinvidic*, 2006]; a short summary of the drilled lithologies; ages according to the geological timescale of *Gradstein and Ogg* [2004]; and correlations with seismic units proposed previously. CCD is the carbonate compensation depth.

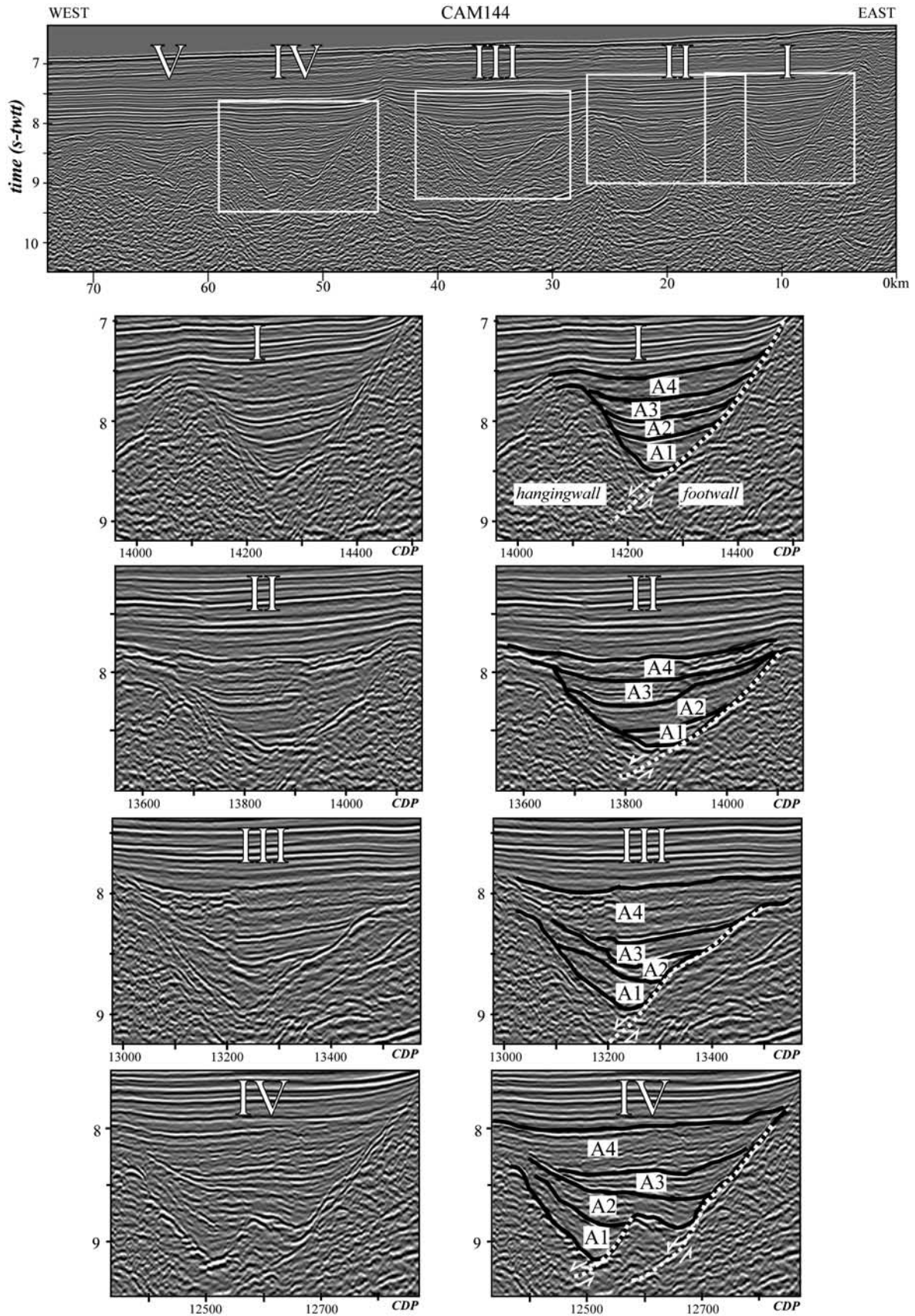


Figure 5

westward (Figure 7). This thickening may result from postbreakup (Albian-Cenomanian) thermal subsidence emphasized within these more oceanic, western domains.

[26] 2. Seismic unit C is characterized by numerous continuous reflections of moderate to high amplitude. Its top is located at the base of the inclined reflectors of unit D and is marked by a continuous reflector with high amplitude. Its base is defined by the downward change to the transparent unit B. The unit lies directly on basement highs, forming onlap sequences accompanied by reflection convergence. Like unit D, unit C has been affected by Cenozoic tectonic events forming folds and faults [Péron-Pinvidic *et al.*, 2007]. Unit C consists of Campanian(?) to lower Oligocene reworked turbidites and pelagic/hemipelagic sediments. This unit thickens toward the southwest, in line with the observed deepening of the acoustic basement in the same direction (Figures 7 and 8). This correlation may indicate differential subsidence during deposition of unit C or simply a deepening of the basin toward the southwest.

[27] 3. Seismic unit D is capped by a prominent reflector with higher amplitude than the reflections of unit E. Local erosional truncations are observed (in the northeast). The main characteristic of unit D is the occurrence of packages of west dipping reflections up to 300 ms two-way traveltimes (twtt) thick at its base and undulating and chaotic reflections at its top (Figure 3). Wilson *et al.* [1996] attributed these inclined reflections to the migration of large deep current beds and/or to variations in sedimentation rate. The sediments forming this unit are composed of early Oligocene to late Miocene pelagic/hemipelagic sediments, contourites and terrigenous turbidites. Its strong westward thinning (Figures 7 and 8) can be attributed to increasing distance from the sedimentary sources generating the turbidites. The sources were probably located on the continental shelf or on the seamounts northeast and east of SIAP.

[28] 4. Seismic unit E is formed by continuous, high-amplitude reflections. Its characteristic structure is a sedimentary wedge onlapping onto a major monoclinical fold in units D and C (Figure 3). This wedge also marks the northeast limit of this unit (Figure 2). Like unit F, it is composed of terrigenous turbidites, but also of pelagic/hemipelagic sediments, that were deposited from late Miocene to early Pleistocene time. Unit E strongly thickens westward of the monoclinical fold affecting unit D (Figure 7). This thickening can be attributed to the presence of deeper depocenters in these regions, compared to the shallower regions to the northeast, where sediments may have been subjected to the action of deep currents preventing the deposition of thicker intervals (e.g., the erosional level characterizing the base of units E, F and E–F).

[29] 5. Seismic unit F corresponds to the upper continuous and subhorizontal reflections above folds affecting deeper units D and C. Its lower limit is defined by a continuous erosional surface with occasionally high seismic amplitude

that marks truncations of unit E reflections. To the west, this unit generally exhibits continuous reflections with variable amplitude, but northeastward it is more chaotic with discontinuous low-amplitude undulating reflections. The unit is composed of Pleistocene terrigenous turbidites thickening northwestward.

[30] 6. Composite seismic unit E–F has been introduced because units E and F cannot be distinguished in the northeast region of the studied area (Figure 2). The composite unit has a chaotic and undulating seismic character. It is often difficult to define its base, which has been mapped following the level at which some truncations of unit D are observed.

3.3. Tectonosedimentary Breccias

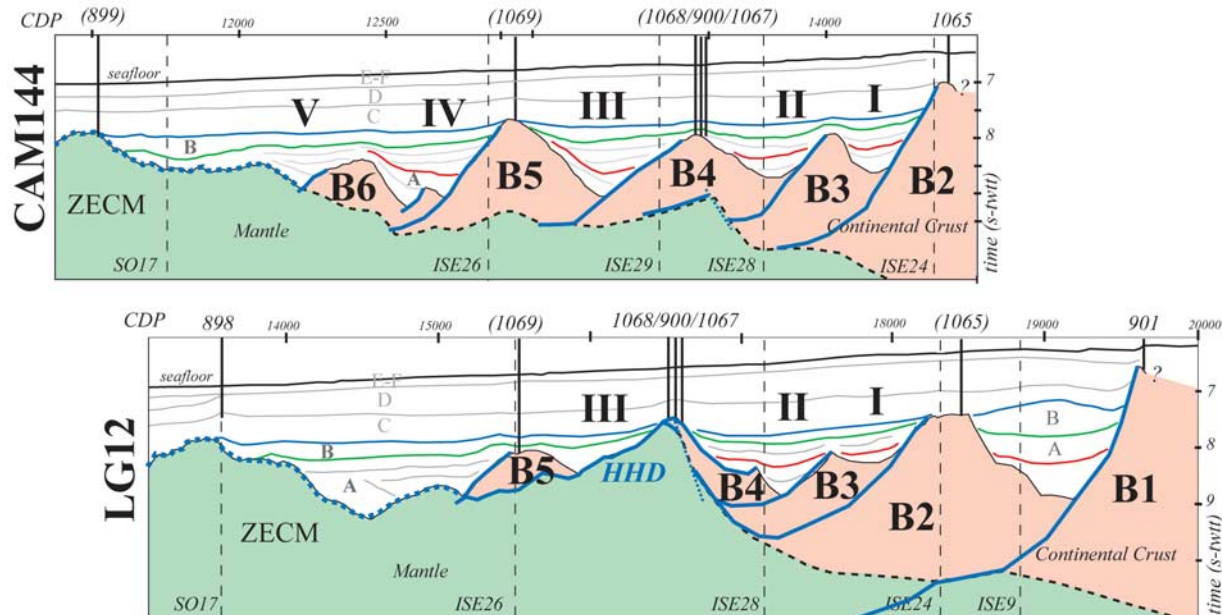
[31] At sites 897 and 899 on the Iberia margin, breccias were recovered and interpreted by Gibson *et al.* [1996] and Comas *et al.* [1996] as mass flow deposits related to submarine slope failure on a large fault scarp. They are composed of reworked serpentinitized peridotite and a minor proportion of basalt clasts. From their mineralogy and geochemistry two types of basalts can be distinguished: basalts with an alkaline affinity and EMOR (mid-ocean ridge) basalts [Cornen *et al.*, 1996]. The close association of these two types of magma is also described from the Galicia Margin further north [Kornprobst *et al.*, 1988] and from Site 1277 [Jagoutz *et al.*, 2007]. These breccias lie within a matrix of late Barremian to early Aptian age [De Kaenel and Bergen, 1996].

[32] At Site 1068, sedimentary breccias were recovered overlying the exhumed HHD (Figure 6) (for a more detailed description, see also Wilson *et al.* [2001, Figure 17]). These grade from matrix-supported to clast-supported breccias downhole and were interpreted by Wilson *et al.* [2001] as mass flows, rockfalls, and talus deposits. The age of the matrix is constrained by nannofossils indicating an imprecise Valanginian to Barremian age (140 to 125 Ma) [Wilson *et al.*, 2001]. The breccias consist of clasts of basement rocks similar to those recovered at ODP sites 900 and 1067. For these basement rocks, independent Ar/Ar dating on plagioclase gave ages of 136 to 137 Ma that were interpreted by Manatschal *et al.* [2001] to correspond to the cooling of these rocks through the $\sim 150^\circ\text{C}$ isotherm during their exhumation to the seafloor. The observation that the breccias are tectonized at their base indicates that they were deposited onto an active fault. Considering all these observations, the most likely interpretation is that these breccias were deposited during activity along HHD after Valanginian and possibly even after Barremian time. However, a precise age of deposition cannot be defined.

[33] At Site 1069, Tertiary and Upper Cretaceous postrift sediments unconformably overlie a thin Lower Cretaceous nannofossil chalk bed with slumped intervals and gravel layers, underlain by a thin layer of Tithonian clay [Wilson *et*

Figure 5. (top) Part of the time-migrated seismic profile CAM144 showing the five successive basins used to define the subunits within unit A (for location, see Figure 1). (bottom) Blowups showing basins I to IV with interpretations showing subunits A1–A4.

a.



b.

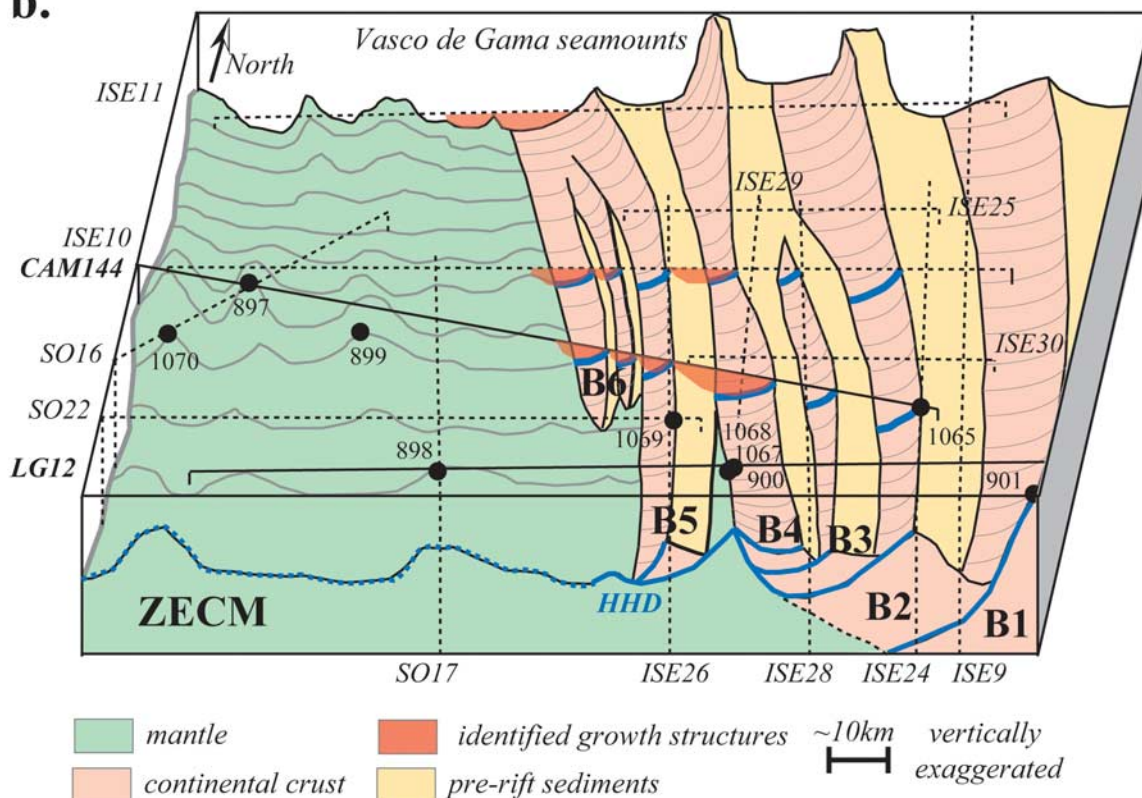


Figure 6. (a) Interpretation of seismic profiles CAM144 and LG12; (b) 3-D schematic representation of the basement structures in the SIAP. Dashed lines mark location of the seismic lines used to construct the diagram (see also Figure 2) and numbers refer to ODP sites. ZECM, zone of exhumed continental mantle; HHD, Hobby High Detachment fault.

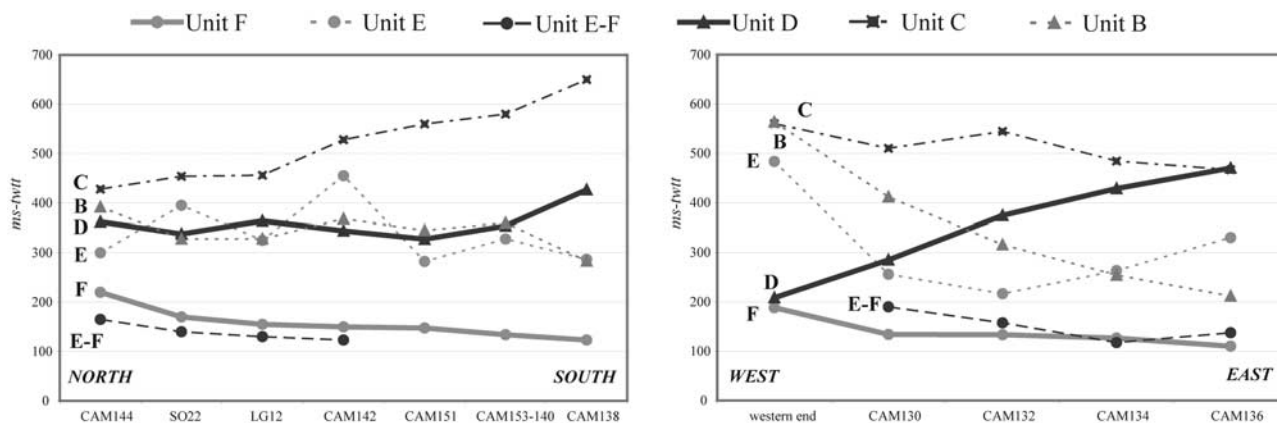


Figure 7. Mean thicknesses of seismic units B to F mapped throughout the SIAP on the various seismic reflection profiles. Each data point represents a mean for an entire seismic profile.

al., 2001]. The occurrence of Tithonian prerift sediments at this site suggests that this high is underlain by continental basement. Of particular importance for this study is the Lower Cretaceous nannofossil chalk bed that was dated as lower Valanginian by *Urquhart* [2001]. These chalks are composed of a faunal assemblage of ostracods and benthic foraminifera thought to be indicative of an open marine, outer shelf to upper slope environment not deeper than 1500 m [*Urquhart*, 2001].

[34] At Site 1070, tectonized breccias with gouge horizons were drilled. These breccias grade downward into massive serpentinitized peridotite intruded by pegmatitic gabbroic veins. The breccias consist of serpentinite and rare gabbro and albitite clasts, poorly sorted and embedded in calcite cement. The fabric of these breccias is very similar to those of Alpine ophicalcites described by *Lemoine et al.* [1987] and was interpreted by *Manatschal et al.* [2001] as tectonic rather than sedimentary in origin. On the basis of geochemical and mineralogical investigations, the gabbro is derived from an EMORB source [*Beard et al.*, 2002; *Hébert et al.*, 2001]. U/Pb dating on zircons from an albitite clast gave an age of 127 ± 4 Ma, interpreted as a crystallization age. This age is compatible with the age estimated on the nearby magnetic anomalies M3 and M1 for the accretion of the crust at this site, which is ~ 124.5 Ma [*Whitmarsh and Wallace*, 2001]. Cooling of this gabbro below 500°C was dated, based on $^{40}\text{Ar}/^{39}\text{Ar}$ on amphiboles, at 119 ± 0.7 Ma [*Manatschal et al.*, 2001]. The $^{40}\text{Ar}/^{39}\text{Ar}$ dating on plagioclase from the same sample gave 110.3 ± 1.3 Ma [*Jagoutz et al.*, 2007], an age which is difficult to interpret because the sediments immediately above the dated sample have been dated as Late Aptian (112 Ma). The large gap between $^{40}\text{Ar}/^{39}\text{Ar}$ plagioclase ages and the recrystallization age observed at Site 1070 is similar to that observed at Site 1277 and will be discussed below.

[35] Site 1277 on the Newfoundland margin corresponds to a basement high that is few kilometers oceanward of magnetic anomaly M1 suggesting an accretion age for the crust of about 127 Ma. Drilling penetrated basalt flows that are intercalated with polymict mass flows and graded sandstones composed of clasts of serpentinitized peridotites and

gabbros identical to the rocks forming the underlying basement [*Müntener and Manatschal*, 2007]. The gabbroic clasts, like those described from sites 897 and 899, show alkaline and EMORB compositions [*Jagoutz et al.*, 2007]. The basement at this high consists of deformed and strongly altered serpentinitized harzburgite with a strong, high-temperature mylonitic foliation that is intruded by igneous veins. Like the clasts in the overlying sediments, the veins are formed by alkaline and EMORB igneous rocks. Although, the breccias drilled at Site 1277 have not been dated, the following observations suggest that they were deposited during or directly after the emplacement of the basement at the seafloor: (1) the clasts in the breccias are fresher than those in the basement, suggesting that these clasts were separated from the fractured and highly permeable basement directly after their exhumation and were deposited, at an early stage, in the less permeable sediments; (2) the intercalations of mass flow and lava flows of enriched MORB composition [*Robertson*, 2007] suggest that these rocks formed in the vicinity of an active spreading center; and (3) the strong analogy with the Aptian breccias drilled at sites 897 and 899 may suggest a similar age for the breccias recovered from Site 1277.

4. Discussion

[36] In sections 2 and 3 we presented the results of detailed mapping of drilled sedimentary units and their relation to basement structures in the deep Iberia-Newfoundland margins. Our results show that the sediments record a complex tectonosedimentary and morphotectonic evolution related to continental breakup. In the following, we first discuss the 3-D architecture of sediment units deposited during and after mantle exhumation. We discuss the spatial variability of the structures in dip and strike profiles, across and along the margin, respectively. In a second part we focus on the tectonic evolution during continental breakup and discuss how these processes are documented by the sedimentary architecture of the margin. Finally, we compare the results obtained in our study with classical concepts

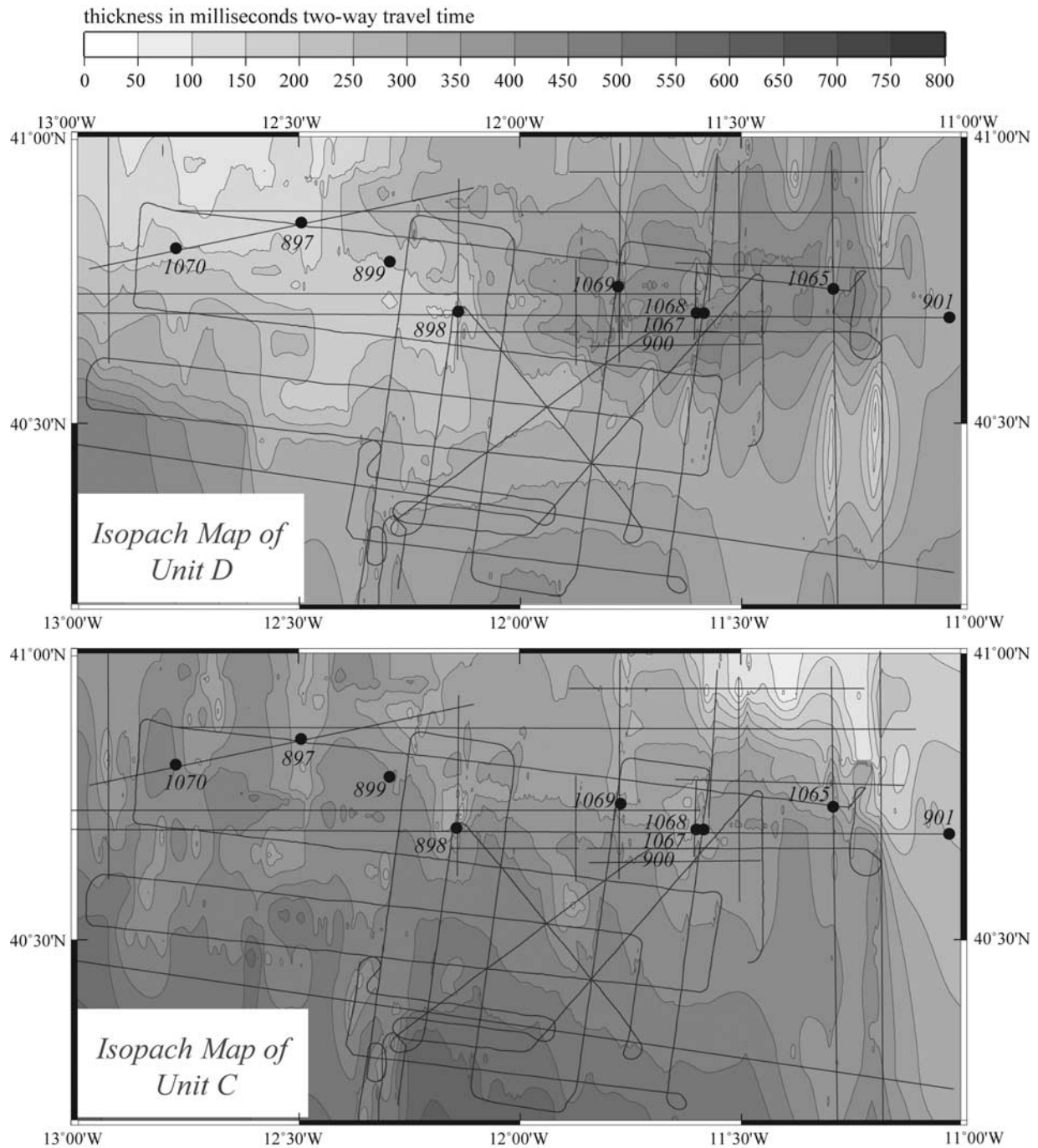


Figure 8. Interpolated isopach maps of units C and D in ms two-way traveltime (twtt). Numbers refer to ODP sites. For contouring, a smooth harmonic surface was fit to the observations [Smith and Wessel, 1990].

commonly used in the interpretation of sedimentary units in rifted margins.

4.1. Three-Dimensional Architecture of Syntectonic Sediments

[37] On a dip section, the geometrical relationships between basement structures and overlying sediments show, at

first glance, the classical relationship between tilted blocks, synrift intervals (unit A) and postrift sediments (unit B) (Figure 9). However, if the nature of crust (continental versus exhumed mantle versus oceanic) is considered, it is clear that classical rift structures (growth structures and tilted blocks) are not limited to the continental crust only. In such circumstances, the application of classical rift

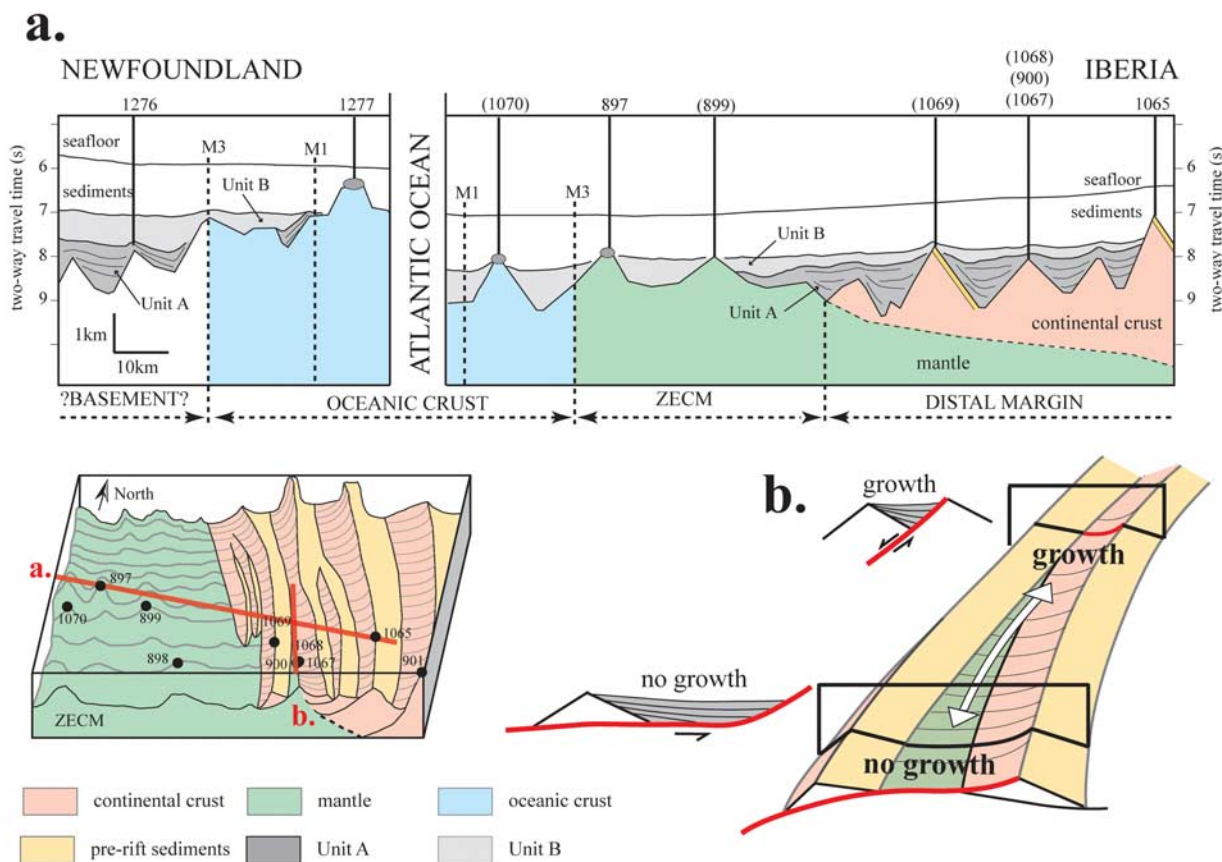


Figure 9. Sedimentary architecture in the Iberia-Newfoundland margins. (a) Section perpendicular to the margin (dip section); (b) schematic section along the margin (for further discussion, see text). Block diagram (from Figure 6b) shows locations of sections. ZECM, zone of exhumed continental mantle.

concepts is likely to lead to misinterpretation of either the age of rifting or the position of the OCT. Our investigations show that although the tectonic evolution of continental breakup documented in the sediments is complex, it is well recorded in unit A. As illustrated in the dip section and discussed in the first part of this paper (Figure 9a), the structures mapped in unit A change across the margin from posttectonic in the east (e.g., subhorizontal reflections in basins I and II on CAM144, Figure 6), to syntectonic further oceanward (e.g., tilted reflections in basins III and IV on CAM144, Figure 6), and to pre-tectonic in the OCT (e.g., occurrence of time-equivalent intervals of unit A drilled on highs and tilted reflections in unit A on the Newfoundland margin, Figure 9a). This observation suggests a migration of the deformation toward the ocean during final rifting and onset of seafloor spreading. Moreover, it shows that, regardless of whether the basement is continental crust, exhumed mantle or oceanic crust, it is affected by wide-spread normal faulting. Unit B can be considered as the first “classical” post-rift sequence that is not affected by extensional processes.

[38] On strike sections, we were able to identify lateral variations in the sedimentary architecture of time-equivalent sedimentary intervals and changes in the geometry of fault and basin architecture (Figure 9b). This distinct observation

is based on careful mapping of the sediment units filling basin III and of the basement blocks D and E bounding this basin across the SIAP (Figure 6). Mapping shows that, in the south, the basin is soled by a detachment fault, the HHD, resulting in a window of exhumed crustal and mantle rocks. This window terminates, along-strike toward the north, and the basin evolves into a classical fault-bounded rift basin. Within this basin, time equivalent sedimentary intervals bearing growth structures in the CAM144 section in the north (subunits A1 and A2) were traced to the south into the LG12 section where no growth structures were observed. In a “classical” interpretation the subunits A1 and A2 would be interpreted as syntectonic in the north (CAM144) and post-tectonic in the south (LG12). However, as our careful seismic reflection tracking shows, subunits A1 and A2 are of the same age throughout the studied area and they were deposited during active displacement along HHD in the south (LG12) contemporaneous to the formation of basins III to V further to the north (CAM 144). We suggest therefore that the lack of growth structures in subunits A1 and A2 on the LG12 section are due to sediment accommodation over a flat detachment that was pulled out at the seafloor. This interpretation is in line with the tectonic overprint of the sedimentary breccias belonging

to unit A drilled at ODP Site 1068 at Hobby High on the LG12 profile (see Figure 6).

4.2. Tectosedimentary and Morphotectonic Evolution of Continental Breakup

[39] Two major tectonic processes can be identified to have controlled mantle exhumation and the subsequent evolution predating the location of the deformation and magmatic activity into a mature oceanic spreading center. One process is controlled by downward concave detachment faults that are interpreted to be responsible for the exhumation of mantle rocks resulting in the formation of the OCT. A second process is manifested by widespread normal faulting that postdates mantle exhumation. This second event (late Aptian/early Albian) predates unit B and seems to be linked to a major magmatic event that is distributed throughout the southern North Atlantic and may be linked to a plate tectonic reorganization. This event is responsible for the tectonometamorphic evolution that is well documented in the more oceanward parts of the OCT in unit A on the Newfoundland margin, and time-equivalent sedimentary breccias drilled at basement highs in the OCT off Iberia. In the following, we discuss the significance of these two episodes and how they are recorded in the sedimentary architecture of the deep Iberia-Newfoundland margins.

4.2.1. Mantle Exhumation (Late Valanginian to Late Aptian)

[40] *Manatschal et al.* [2001] proposed, based on a kinematic inversion of the LG12 section, that the crust was already thinned to less than 10 km by Tithonian time and that the geometry of the faults active during final rifting changed from upward to downward concave (for a more detailed discussion, see also *Manatschal* [2004]). On the basis of the detailed mapping of the sediments in SIAP, we are now able to demonstrate how the transition from upward to downward concave faults during final rifting is documented in the sedimentary architecture. Figure 10 illustrates the reconstructed LG12 and CAM144 sections for the onset of final rifting dated as Tithonian (150–145 Ma), the end of the deposition of subunit A2, and the base of unit B (late Aptian to early Albian) that represents the end of tectonic activity and is related to the Atlantic Ocean opening between Iberia and Newfoundland.

[41] The pre-faulting stage is constrained in the SIAP by Tithonian limestones and claystones showing outer shelf environments drilled at ODP sites 901, 1065 and 1069 [*Wilson et al.*, 2001; *Urquhart*, 2001]. The fact that shallow water limestones of Tithonian age were also drilled at ODP Site 639 at the Deep Galicia margin further to the north suggests that Tithonian age sediments were deposited across the entire future distal margin, forming a large platform. The occurrence of such a shallow water platform shows that before Tithonian time the future distal margin was little affected by high-angle faulting, despite the strong evidence that the crust was by that time already thinned to less than 10 km [*Manatschal et al.*, 2001].

[42] The mantle exhumation stage is difficult to date, but based on the available drilling results, final rifting seems to be associated with strong subsidence and exhumation pro-

cesses. A major deepening of the basin from a restricted shelf environment during Tithonian to an open marine, outer shelf to upper slope environment of less than 1500 m water deep is documented by the nannofossil chalk bed drilled at Site 1069 over a basement high [*Urquhart*, 2001]. Higher subsidence rates can be expected for the adjacent fault-bounded basins. The evidence for exhumation along detachment faults is mainly documented by drilling at sites 900, 1067 and 1068 over Hobby High [*Manatschal et al.*, 2001]. On the basis of structural observations and $^{40}\text{Ar}/^{39}\text{Ar}$ ages, it was proposed that the rocks drilled at sites 900, 1067 and 1068 were exhumed along a downward concave fault toward the seafloor. During exhumation the tectonized basement drilled at sites 900 and 1067 acted as source for the sedimentary breccia drilled at Site 1068. These basement clasts were deposited within a sedimentary matrix dated as Valanginian to Barremian (~140–125 Ma) [*Manatschal et al.*, 2001]. The tectonic overprint of the sedimentary breccia toward its contact to the underlying mantle [*Wilson et al.*, 2001, Figure 17] suggests that the sedimentary breccia was deposited onto the active HHD detachment. Activity along this fault occurred around 137 Ma (late Valanginian), which is the time when the basement rocks drilled at sites 900 and 1067 were cooled below 150°C.

[43] The temporal and spatial evolution of final rifting is also documented in the sedimentary architecture of unit A in the LG12 and CAM144 sections. The major features that can be observed are that subunits A1 and A2 form well-imaged growth structures in basins III and IV in the CAM section whereas such structures are neither observed in the adjacent basins I and II in CAM144 nor in the LG12 sections. In these sections, the time-equivalent reflections are parallel and flat and onlap onto the adjacent basement highs. These observations, illustrated in Figure 10, can be explained by a migration of deformation from the east to the west, i.e., from more continentward parts toward the future ocean, and from south to north, i.e., parallel to the propagation of the ocean.

[44] Dating the migration of deformation based on growth structures is, however, hampered by the observation that growth structures are only valuable indicators for syntectonic deposition in classical rift basins bounded by high-angle faults. In the SIAP, we argue that such classical high-angle normal faults can evolve along-strike into low-angle top basement detachment faults. Therefore the apparent migration of rift activity toward the north may be an artefact reflecting the changing mode of deformation from upward to downward concave faults along strike rather than dating the age of active faulting. For the LG12 section, *Manatschal* [2004] proposed that high-angle upward concave faults develop, through time, into downward concave faults [see *Manatschal*, 2004, Figure 13]. Such a development would imply that structures that are active, at a given time along the margin, overprint each other in sections perpendicular to the margin. This observation explains the link between the spatial and temporal evolution of structures documented in the 3-D sedimentary architecture of deep margins and shows that there is a strong link between fault geometry, basin architecture and sedimentary structures.

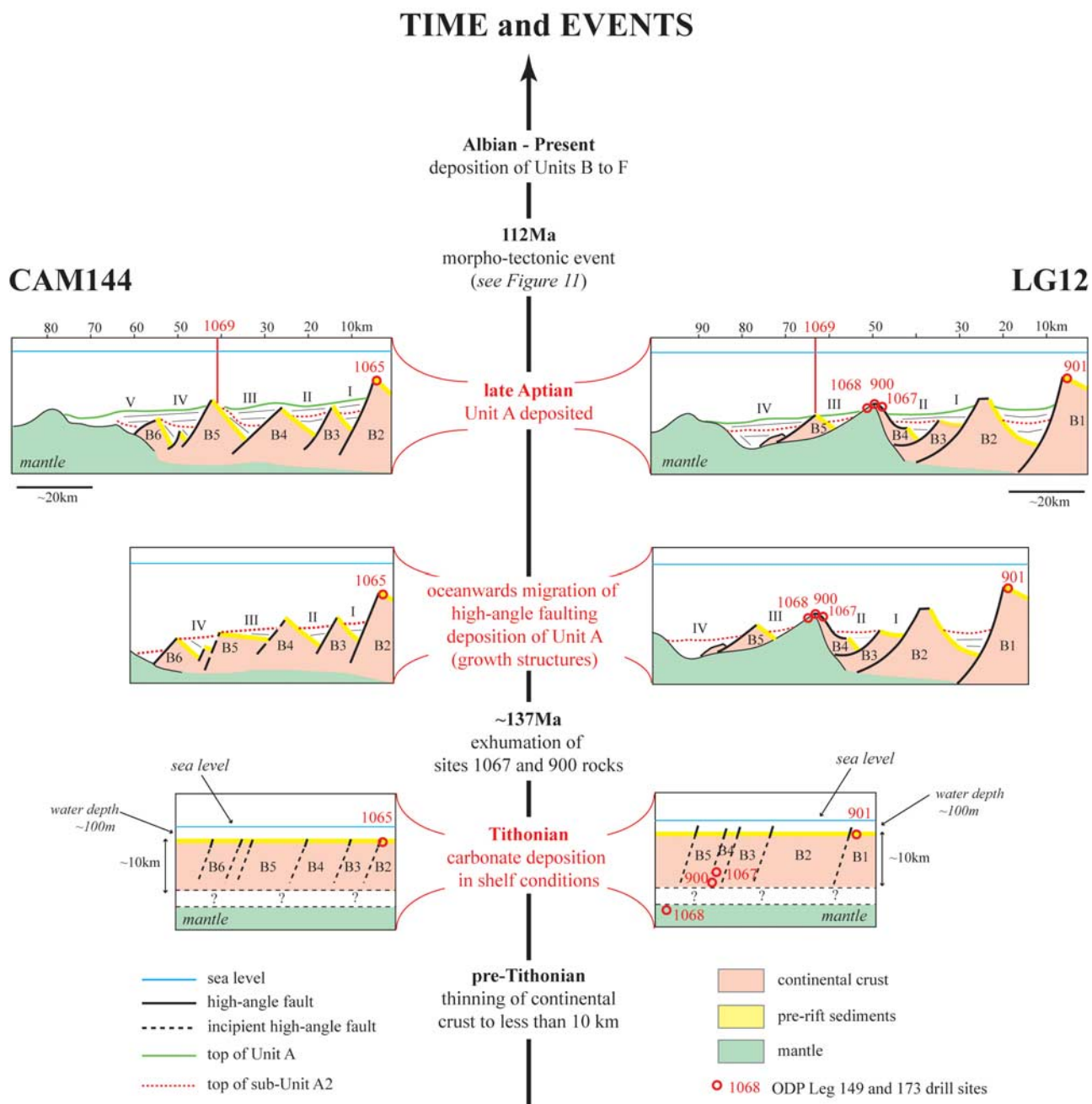


Figure 10. Temporal and spatial evolution of sediment deposition in the SIAP inferred from the structural restoration of the LG12 and CAM144 seismic sections.

4.2.2. OCT Morphotectonic Evolution (Late Aptian–Early Albian)

[45] A comparison of the sedimentary breccias drilled at sites 897 and 899 and dated as Aptian with those drilled at Site 1277 on the conjugate Newfoundland margin shows that they share many similarities. A key observation is that they contain mafic clasts, derived from EMORB and alkaline magmas. Dating of EMORB igneous rocks at sites 1070 and 1277 gave ages similar to those expected from the accretion age of the underlying crust [Beard *et al.*, 2002].

Alkaline igneous rocks forming magmatic veins at Site 1277 and sills at Site 1276 gave ages of 113 ± 2 Ma and younger [Jagoutz *et al.*, 2007]. Thus the magmatic system that affected the OCT is complex and polyphase. Because at Site 1277, the breccias contain clasts of the alkaline magmas dated as early Albian and are overlapped by unit B which is Albian to Cenomanian in age, the age of the highs must coincide with or postdate the emplacement of alkaline magmas and predate the onset of deposition of unit B. That dates the formation of the highs as late Aptian to early

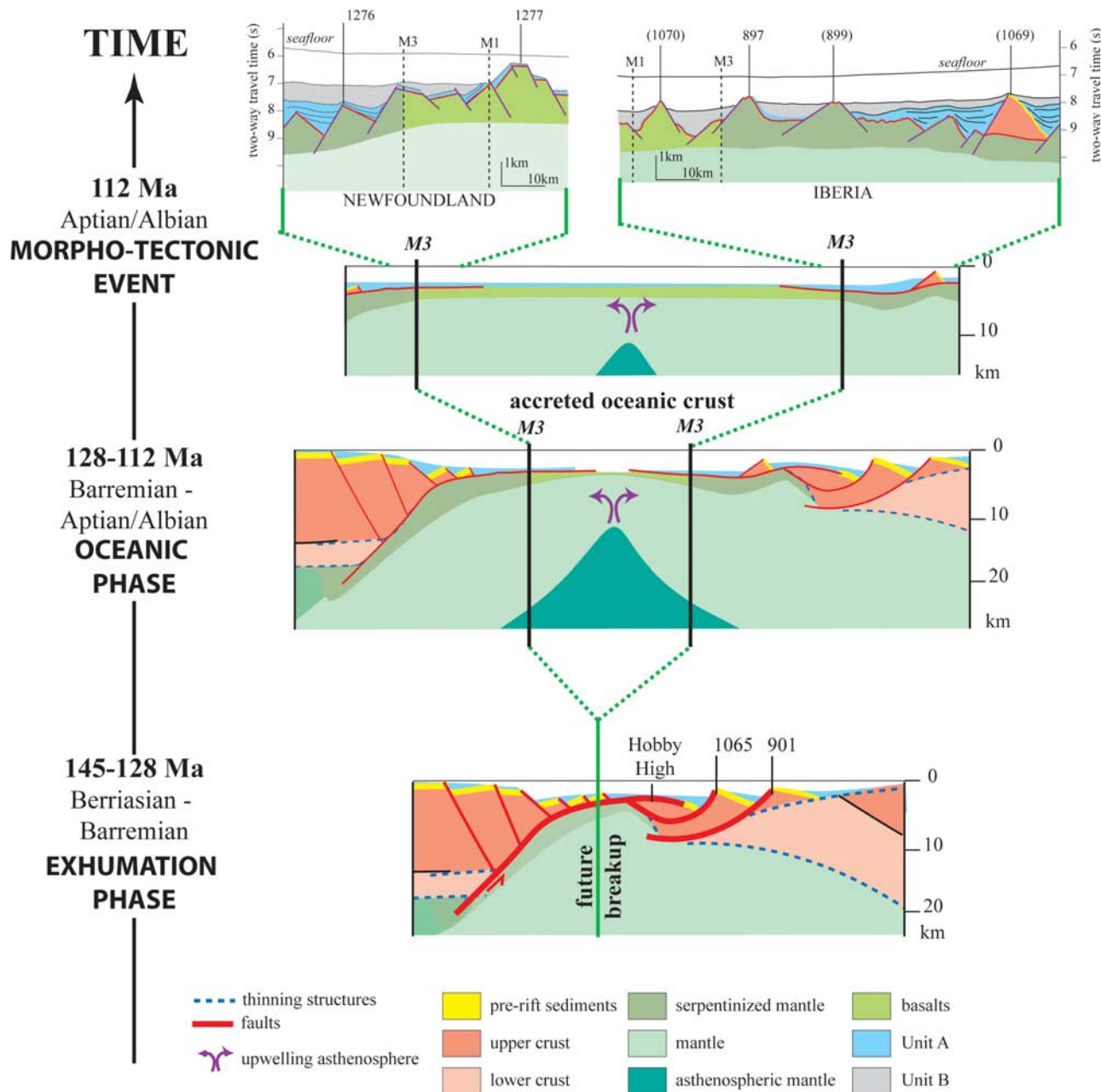


Figure 11. A conceptual model illustrating the temporal and spatial evolution of continental breakup in the Iberia-Newfoundland margins.

Albian (~112 Ma). Although no evidence for the uplift of highs is observed in seismic sections from the OCT in the SIAP (unit A is too thin to be imaged in seismic sections), on the conjugate Newfoundland margin there are geometrical relationships between units A and B that support such a late Aptian/early Albian event: Between sites 1276 and 1277 in the Newfoundland margin, unit A presents continentward tilted reflections that are overlapped by reflections belonging to unit B (Figure 1c). Although the overall mechanism of tilting is not yet understood, the fact that

the breakaways of successive faults are more elevated going oceanward may indicate that this event is associated with a large-scale up-warping of the previously exhumed and accreted mantle lithosphere.

[46] On the basis of the mapped sediment architecture and stratigraphic ages obtained for units A and B suggesting that M3 (128 Ma) dates the onset of seafloor spreading, we envisage the following tectonomagmatic evolution (Figure 11). After exhumation leading to the formation of a wide zone of exhumed mantle (136 to

128 Ma), accretion of oceanic crust started at 128 Ma and continued for about 10 m.y. Seafloor spreading during this initial stage is documented by magnetic anomalies M3 to M0 and the formation of EMORB basalts that were sampled as clasts in mass flows at sites 897, 899 and 1277. During the final deposition of unit A, deformation spread out over previously accreted oceanic crust to cover a region more than 200 km wide overall, suggesting a transient reduction or even cessation of seafloor spreading activity at the ridge. The reason for the delocalization of the deformation is not yet understood, but it seems that it occurred during or shortly before a major magmatic event that is documented throughout the southern North Atlantic. Local evidence for such an event are (1) sills that were drilled at Site 1276 coincide on the Newfoundland side with a strong reflection (the U reflection) that is also observed in the SIAP; (2) the thermal perturbation that is recorded by $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages on plagioclase in 128 Ma old gabbros drilled at Site 1070 (the age of 110.3 ± 1.1 Ma, interpreted as a cooling age is younger than the overlying sediments and cannot be interpreted as a simple cooling related to exhumation); and (3) the occurrence of Aptian mass flows drilled and seismically imaged on several highs. Thus our observations suggest that the morphotectonic phase leading to the basement topography observed in the OCT of the Iberia-Newfoundland margin is related to a major tectonomagmatic event that may be, in turn, linked to a major plate tectonic reorganization. *Tucholke et al.* [2007] called this event the “Aptian event” and interpreted it as resulting from the final separation of subcontinental lithosphere due to the rising asthenosphere initiating seafloor spreading. Further research is necessary to better understand the nature of this event.

5. Conclusions and Implications

[47] The aim of our study was to investigate how the processes related to continental breakup are recorded in the 3-D sedimentary architecture of the conjugate Iberia-Newfoundland margins. Our results show that this architecture records a complex tectonosedimentary and morphotectonic evolution that supports the idea that continental breakup in magma-poor margins is distributed in time and space, lasting for more than 20 m.y. and resulting in the accretion of 40–170 km of crust that is neither oceanic nor continental.

[48] On the basis of mapping of dated seismic units and borehole data we were able to identify two major phases: a first one, dated as Tithonian to Barremian (145–128 Ma) that is related to exhumation of crustal and mantle rocks along downward concave detachment faults; and a second one, dated as latest Aptian (112 Ma) that is responsible for the formation of the observed basement topography. The sedimentary evolution associated with these deformation phases is documented by a complex tectonosedimentary and morphotectonic evolution that is controlled by the fault geometry and basin architecture, both of which are strongly three-dimensional. This observation, together with the complex breakup history, has some major implications for the determination of syntectonic sedimentary intervals and the

interpretation of age and location of continental breakup. From this point of view, the following concepts are of particular importance and have some wider implications for the study of deep margins:

[49] 1. The occurrence of growth structures is only a valuable indicator for syntectonic deposition in classical rift basins bounded by high-angle faults but cannot be used as criteria to interpret syntectonic intervals in deep margins where part of the extension is accommodated by low-angle top-basement detachment faults. The only way to properly identify syntectonic intervals is to map them in 3-D toward faulted blocks.

[50] 2. The subdivision into prerift, synrift, and postrift (tectonic) sediments is hampered by the fact that rifting is polyphase, rift activity migrates and the mode of rifting changes through time. If this classical subdivision is applied to the deep Iberia/Newfoundland margins, the Tithonian time interval would represent the prerift, unit B the postrift and unit A would represent a transition from prerift to postrift including the synrift sequence. The first postrift sequence identifiable on seismic sections (unit B) does not coincide with the first occurrence of oceanic crust (in the SIAP commonly interpreted as M3, 128 Ma) but more likely with the mechanical decoupling between two lithospheric plates and the irreversible localization of spreading within a spreading center, which for the Iberia/Newfoundland margins is interpreted to occur at the Aptian/Albian (112 Ma) boundary.

[51] 3. By definition, a breakup unconformity is a specific stratigraphic contact separating older from younger sediments, marking a nondeposition, erosional or an angular unconformity forming a significant hiatus [*Falvey, 1974; Mitchum, 1977; Driscoll et al., 1995*]. It is equivalent on seismic sections to a specific seismic reflector that marks changes in reflectivity, amplitude or geometry. In the way it was defined, it is time equivalent to the onset of seafloor spreading and results from the mechanical rebound due to continental breakup. In our view, this original definition of breakup unconformity is unsuitable for the deep Iberia-Newfoundland margins because it does not take into account the complex morphotectonic evolution of the OCT. In previous studies, the late Aptian to early Albian event that coincides with the limit between unit A and unit B was proposed to represent the breakup unconformity (e.g., orange reflection at the DSDP Site 398 and U reflector on the Newfoundland conjugate margin [*Groupe Galice, 1979; Mauffret and Montadert, 1987; Tucholke et al., 2007*]). However, our observations suggest that this limit is rather associated with the widespread delocalization of deformation and the emplacement of alkaline magma over the conjugate deep margins rather than to the beginning of oceanic accretion.

[52] **Acknowledgments.** The authors wish to thank J. Hopper, F. Tsikalas and G. Bertotti for their helpful reviews that permitted to improve the manuscript. This work was supported by the Royal Society through a Joint Project Grant. G.M. and G.P.P. thank the GDR Marges. G.P.P. thanks the EU and the Marie Curie grant program. This research used samples and/or data provided by the Ocean Drilling Program (ODP). ODP was sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc.

References

- Beard, J. S., P. D. Fullagar, and K. Sinha (2002), Gabbroic pegmatite intrusions, Iberia Abyssal Plain, ODP Leg 173, Site 1070: Magmatism during a transition from non-volcanic rifting to sea-floor spreading, *J. Petrol.*, 43–5, 885–905.
- Beslier, M. O. (1996), Data report: Seismic line LG12 in the Iberia Abyssal Plain, *Proc. Ocean Drill. Program Sci. Results*, 149, 737–739.
- Boillot, G., et al. (1987), *Proceedings of the Ocean Drilling Program, Initial Reports*, vol. 103, Ocean Drill. Program, College Station, Tex.
- Boillot, G., J. Girardeau, and J. Kornprobst (1989), Rifting of the West Galicia continental margin: A review, *Bull. Soc. Geol. Fr.*, 8(4), 393–400.
- Chevalier, F., M. Guiraud, J.-P. Garcia, J.-L. Dommergues, D. Quesne, P. Allemand, and T. Dumont (2003), Calculating the long-term displacement rates of a normal fault from the high-resolution stratigraphic record (early Tethyan rifting French Alps), *Terra Nova*, 15(6), 410–416.
- Comas, M. C., M. Sanchez-Gomez, G. Cornen, and E. De Kaenel (1996), Serpentinized peridotite breccia and olitostrome on basement highs of the Iberia Abyssal Plain: Implications for tectonic margin evolution, *Proc. Ocean Drill. Program Sci. Results*, 149, 577–591.
- Comen, G., M. O. Beslier, and J. Girardeau (1996), Petrology of the mafic rocks cored in the Iberia Abyssal Plain, *Proc. Ocean Drill. Program Sci. Results*, 149, 449–469.
- Cowie, P. A., J. R. Underhill, M. D. Behn, J. Lin, and C. E. Gill (2005), Spatio-temporal evolution of strain accumulation derived from multi-scale observations of Late Jurassic rifting in the northern North Sea: A critical test of models for lithospheric extension, *Earth Planet. Sci. Lett.*, 234(3–4), 401–419.
- Decandia, F. A., and P. Elter (1972), La “zona” ofiolitífera del Bracco nel sottopiede compreso fra Levanto e la Val Graveglia (Appennino ligure), *Mem. Soc. Geol. Ital.*, 11, 503–530.
- De Kaenel, E., and J. A. Bergen (1996), Mesozoic calcareous nanofossil biostratigraphy from sites 897, 899, and 901, Iberia Abyssal Plain: New biostratigraphic evidence, *Proc. Ocean Drill. Program Sci. Results*, 149, 27–59.
- Discovery 215 Working Group (1998), Deep structure in the vicinity of the ocean-continent transition zone under the southern Iberia Abyssal Plain, *Geology*, 26, 743–746.
- Driscoll, N. W., J. R. Hogg, N. Christie-Blick, and G. Karner (1995), Extensional tectonics in the Jeanne d’Arc Basin, offshore Newfoundland: Implications for the timing of break-up between Grand Banks and Iberia, in *The Tectonics, Sedimentation and Paleoceanography of the North Atlantic Region*, edited by R. A. Scrutton, G. B. Shimmiel, and A. W. Tudhope, *Geol. Soc. Spec. Publ.*, 90, 1–28.
- Falvey, D. A. (1974), The development of continental margins in plate tectonic theory, *APEA J.*, 14, 95–106.
- Gibson, I. L., K. L. Miliken, and J. K. Morgan (1996), Serpentinite-breccia landslide deposits generated during crustal extension at the Iberia Margin, *Proc. Ocean Drill. Program Sci. Results*, 149, 571–575.
- Gradstein, F. M., and J. G. Ogg (2004), Geologic time scale 2004: Why, how, and where next!, *Lethaia*, 37, 175–181.
- Groupe Galice (1979), The continental margin off Galicia and Portugal: Acoustical stratigraphy, dredge stratigraphy, and structural evolution, *Initial Rep. Deep Sea Drill. Proj.*, 47, Part 2, 633–662.
- Henning, A. T., D. S. Sawyer, and D. C. Templeton (2004), Exhumed upper mantle within the ocean-continent transition on the northern West Iberia margin: Evidence from prestack depth migration and total tectonic subsidence analyses, *J. Geophys. Res.*, 109, B05103, doi:10.1029/2003JB002526.
- Hébert, R., K. Guedari, M. R. Lafliche, M. O. Beslier, and V. Gardien (2001), Petrology and geochemistry of exhumed peridotites and gabbros at non-volcanic margins: ODP Lag 173, West Iberia ocean-continent transition zone, in *Non-volcanic Rifting of Continental Margins: A Comparison of Evidence From Land and Sea*, edited by R. C. L. Wilson et al., *Geol. Soc. Spec. Publ.*, 187, 161–190.
- Jagoutz, O., O. Müntener, G. Manatschal, B. D. Turrin, and I. M. Villa (2007), The rift-to-drift transition in the North Atlantic: A stuttering start of the MORB machine?, *Geophys. Res. Abstr.*, 9, 03623, EGU2007-A-03623.
- Kornprobst, J., P. Vidal, and J. Malod (1988), Les basaltes de la marge de Galice (Nord de la Péninsule Ibérique): Hétérogénéité des spectres de terres rares à la transition continent/océan. Données géochimiques préliminaires, *C. R. Acad. Sci., Ser. 2*, 306, 1359–1364.
- Lavier, L., and G. Manatschal (2006), A mechanism to thin the continental lithosphere at magma-poor margins, *Nature*, 440, 324–328.
- Lemoine, M., P. Tricart, and G. Boillot (1987), Ultramafic and gabbroic ocean floor of the Ligurian tethys (Alps, Corsica, Apennines): In search of a genetic model, *Geology*, 15, 622–625.
- Lister, G. S., M. A. Etheridge, and P. A. Symonds (1986), Detachment faulting and the evolution of passive continental margins, *Geology*, 14, 246–250.
- Manatschal, G., N. Froitzheim, M. Rubenach, and B. D. Turrin (2001), The role of detachment faulting in the formation of an ocean-continent transition: Insights from the Iberia Abyssal Plain, in *Non-volcanic Rifting of Continental Margins: A Comparison of Evidence From Land and Sea*, edited by R. C. L. Wilson et al., *Geol. Soc. Spec. Publ.*, 187, 405–428.
- Mauffret, A., and L. Montadert (1987), Rift tectonics on the passive continental margin off Galicia (Spain), *Mar. Pet. Geol.*, 4, 49–70.
- Mauffret, A., and L. Montadert (1988), Seismic stratigraphy off Galicia, *Proc. Ocean Drill. Program Sci. Results*, 103, 13–30.
- Manatschal, G. (2004), New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps, *Int. J. Earth Sci.*, 93, 432–466.
- McKenzie, D. (1978), Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, 40, 25–32.
- Mitchum, R. M. (1977), Seismic stratigraphy and global changes of sea level, Part 11 Glossary of terms used in seismic stratigraphy, in *Seismic Stratigraphy: Application to Hydrocarbon Exploration*, edited by C. E. Clayton, *AAPG Memoir*, 26, 205–212.
- Müntener, O., and G. Manatschal (2007), High degrees of melt extraction recorded by spinel harzburgite of the Newfoundland margin: The role of inheritance and consequences for the evolution of the southern North Atlantic, *Earth Planet. Sci. Lett.*, 252, 437–452, doi:10.1016/j.epsl.2006.10.009.
- Murillas, J., D. Mougnot, G. Boillot, M.C. Comas, E. Banda, and A. Mauffret (1990), Structure and evolution of the Galicia Interior Basin (Atlantic western Iberian continental margin), *Tectonophysics*, 184, 297–319.
- Péron-Pinvidic, G. (2006), Morphotectonique et architecture sédimentaire dans la Transition Océan Continent de la marge ibérique, Ph.D. thesis, Louis Pasteur Univ., Strasbourg, France.
- Péron-Pinvidic, G., G. Manatschal, S. Dean, and T. Minshall (2007), Compressional structures on the West Iberia rifted margin: What controls their distribution?, in *The Nature and Origin of Compression in Passive Margins*, *Geol. Soc. Spec. Publ.*, in press.
- Pickup, S. L. B., R. B. Whitmarsh, C. M. R. Fowler, and T. J. Reston (1996), Insight into the nature of the ocean-continent transition off West Iberia from a deep multichannel seismic reflection profile, *Geology*, 24, 1079–1082.
- Robertson, A. H. F. (2007), Earliest formed slow spreading rifted oceanic crust: Sedimentary, igneous and structural evidence from the Newfoundland rifted margin, *Proc. Ocean Drill. Program Sci. Results [CD-ROM]*, 210, in press.
- Roeser, H. A., G. Eilers, J. Fritsch, H. Keppler, P. Kewitsch, A. Klein, L. Pinheiro, and B. Schreckenberger (1992), SONNE Cruise S0–75: Geophysical investigations of the crustal structure of the North Atlantic off Portugal, final report of the geophysical legs of the SONNE cruise SO-75, 14 October 1991–12 November 1991, Bundesminister für Forschung und Technol., Hannover, Germany.
- Russell, S. M., and R. B. Whitmarsh (2003), Magmatism at the west Iberia non-volcanic rifted continental margin: Evidence from analyses of magnetic anomalies, *Geophys. J. Int.*, 154, 706–730.
- Sawyer, D. S., et al. (1994), *Proceedings of the Ocean Drilling Program, Initial Reports*, vol. 149, Ocean Drill. Program, College Station, Tex.
- Shipboard Scientific Party (2004), Leg 210 summary, *Proc. Ocean Drill. Program Initial Rep.*, 210, 1–78.
- Sibuet, J. C., et al. (1979), *Initial Reports of the Deep Sea Drilling Project*, vol. 47, Part 2, U. S. Govt. Print. Off., Washington, D. C.
- Sibuet, J. C., S. Srivastava, M. Enachescu, and G. D. Karner (2007), Lower Cretaceous motion of Flemish Cap with respect to North America: Implications on the formation of Orphan Basin and SE Flemish Cap/Galicia Bank conjugate margins, in *Imaging, Mapping and Modeling Lithospheric Extension*, edited by G. D. Karner, G. Manatschal, and L. Pinheiro, *Geol. Soc. Spec. Publ.*, 282, in press.
- Smith, W. H. F., and P. Wessel (1990), Gridding with continuous curvature splines in tension, *Geophysics*, 55, 293–305.
- Srivastava, S. P., J. Verhoef, and R. Macnab (1988), Results from a detailed aeromagnetic survey across the northeast Newfoundland margin, part I: Spreading anomalies and relationship between magnetic anomalies and the ocean-continent boundary, *Mar. Pet. Geol.*, 5, 306–323.
- Srivastava, S. P., J. C. Sibuet, S. Cande, W. R. Roest, and I. D. Reid (2000), Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins, *Earth Planet. Sci. Lett.*, 182, 61–76.
- Tucholke, B. E., D. S. Sawyer, and J. C. Sibuet (2007), Breakup of the Newfoundland-Iberia rift, in *Imaging, Mapping and Modeling Lithospheric Extension*, edited by G. D. Karner, G. Manatschal, and L. Pinheiro, *Geol. Soc. Spec. Publ.*, 282, in press.
- Urquhart, E. (2001), Depositional environment of syn-rift sediments on the Iberia margin, *Eos Trans. AGU*, 82(47), Fall Meet. Suppl., Abstract PP42B-0505.
- Wernicke, B. (1985), Uniform-sense normal simple shear of the continental lithosphere, *Can. J. Earth Sci.*, 22, 108–125.
- Whitmarsh, R. B., and P. R. Miles (1995), Models of the development of the West Iberia rifted continental margin at 40°30’N deduced from surface and deep-tow magnetic anomalies, *J. Geophys. Res.*, 100, 3789–3806.
- Whitmarsh, R. B., and D. S. Sawyer (1996), The ocean-continent transition beneath the Iberia Abyssal Plain and continental rifting to seafloor spreading processes, *Proc. Ocean Drill. Program Sci. Results*, 149, 713–733.
- Whitmarsh, R. B., and P. J. Wallace (2001), The rift-to-drift development of the West Iberia nonvolcanic continental margin: A summary and review of the contribution of Ocean Drilling Program Leg 173, *Proc. Ocean Drill. Program Sci. Results*, 173, 1–36.
- Whitmarsh, R. B., et al. (1998), *Proceedings of the Ocean Drilling Program, Initial Reports*, vol. 173, Ocean Drill. Program, College Station, Tex.

- Whitmarsh, R. B., G. Manatschal, and T. A. Minshull (2001), Evolution of magma-poor continental margins from rifting to seafloor spreading, *Nature*, 413, 150–154.
- Wilson, R. C. L., D. S. Sawyer, R. B. Whitmarsh, J. Zerong, and J. Carbonell (1996), Seismic stratigraphy and tectonic history of the Iberia Abyssal Plain, *Proc. Ocean Drill. Program Sci. Results*, 149, 617–630.
- Wilson, R. C. L., G. Manatschal, and S. Wise (2001), Rifting along non-volcanic passive margins: Strati-

graphic and seismic evidence from the Mesozoic successions of the Alps and western Iberia, in: *Non-volcanic Rifting of Continental Margins: A Comparison of Evidence From Land and Sea*, edited by R. C. L. Wilson, R. B. Whitmarsh, B. Taylor and N. Froitzheim, *Geol. Soc. Spec. Publ.*, 187, 429–452.

G. Manatschal and G. Péron-Pinvidic, IPGS/CGS-EOST, 1 rue Blessig, F-67084 Strasbourg Cedex, France.

(gwenn.peron-pinvidic@east.u-strasbg.fr; manatschal@illite.u-strasbg.fr)

T. A. Minshull, School of Ocean and Earth Science, NOC, European Way, Southampton SO14 3ZH, UK. (tmin@noc.soton.ac.uk)

D. S. Sawyer, Department of Earth Science, Rice University, 6100 Main Street, Houston, TX 77005-1892, USA. (dale@rice.edu)