Extensional tectonics in the Jeanne d'Arc Basin, offshore Newfoundland: implications for the timing of break-up between Grand Banks and Iberia

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Abstract: Using seismic reflection and exploratory well data from the Jeanne d'Arc basin, offshore Newfoundland, we examined the link between unconformity generation and the onset of seafloor spreading between the central Grand Banks and Iberia. A prominent unconformity developed across the entire basin, previously interpreted as a 'break-up' unconformity, is reinterpreted as a late Barremian/early Aptian rift-onset unconformity on the basis of the stratal geometry and lithofacies. The rotation and divergence of seismic reflectors above this unconformity attest to differential subsidence documenting an episode of extension and block rotation within the basin at this time. Our seismic sequence analysis suggests that rifting and block rotation continued in the Jeanne d'Arc basin until at least late Aptian/early Albian time.

The onset of seafloor spreading between the central Grand Banks and Iberia is uncertain because of limited marine magnetic and drilling data (ODP & DSDP), and the existence of the Cretaceous magnetic quiet zone along the margin. However, recent studies indicate that magnetic anomaly M0 (118 Ma) is not well resolved north of the Newfoundland Seamounts within the Newfoundland basin and is not present north of the Figueiro fracture zone along the conjugate Iberian margin. This suggests that seafloor spreading between the northern portion of the Newfoundland basin and the northern Iberian margin began after the early Aptian. Given that the cessation of rifting marks the onset of seafloor spreading our seismic sequence analysis indicates that the onset of seafloor spreading in the northern Newfoundland basin, north of the Newfoundland Seamounts, began after late Aptian time.

The sedimentary record along passive margins is punctuated by unconformities (Vail *et al.* 1977; Vail 1987). An unconformity, as defined by Mitchum (1977), is a surface separating older from younger strata, along which there is evidence of nondeposition or erosion (subaerial and/or submarine) with a significant hiatus indicated. Subsequently, Posamentier *et al.* (1988) and Van Wagoner *et al.* (1988) defined an unconformity as a surface separating older from younger strata, along which there is evidence of truncation by subaerial erosion (and possibly correlative submarine erosion) or subaerial exposure, with a hiatus indicated. This definition of unconformity is more restrictive than the definition used by Mitchum (1977), thereby limiting the usage of the term. In this study, we adhere to the more general definition of unconformity proposed by Mitchum (1977) because it is not always possible to discern whether a submarine erosional or non-depositional surface is correlative with, or necessarily implies, subaerial exposure or erosion.

Along many passive continental margins, the unconformity that is approximately time-equivalent to the onset of seafloor spreading has been termed the break-up unconformity (Falvey 1974). Determining the onset of seafloor spreading on the basis of marine magnetic and drilling data at some passive margins is difficult owing to the existence of magnetic quiet zones and thick wedges of clastic sediment overlying basement. In many instances, the age of the break-up unconformity ascertained from seismic reflection and drilling data is used as a proxy for estimating the time at which rifting ceased and seafloor spreading began (Falvey 1974; Hubbard *et al.* 1985; Tankard & Welsink 1987; Boillot & Winterer 1988; Meador & Austin 1988; Meador *et al.* 1988; Austin *et al.* 1989; Tankard *et al.*

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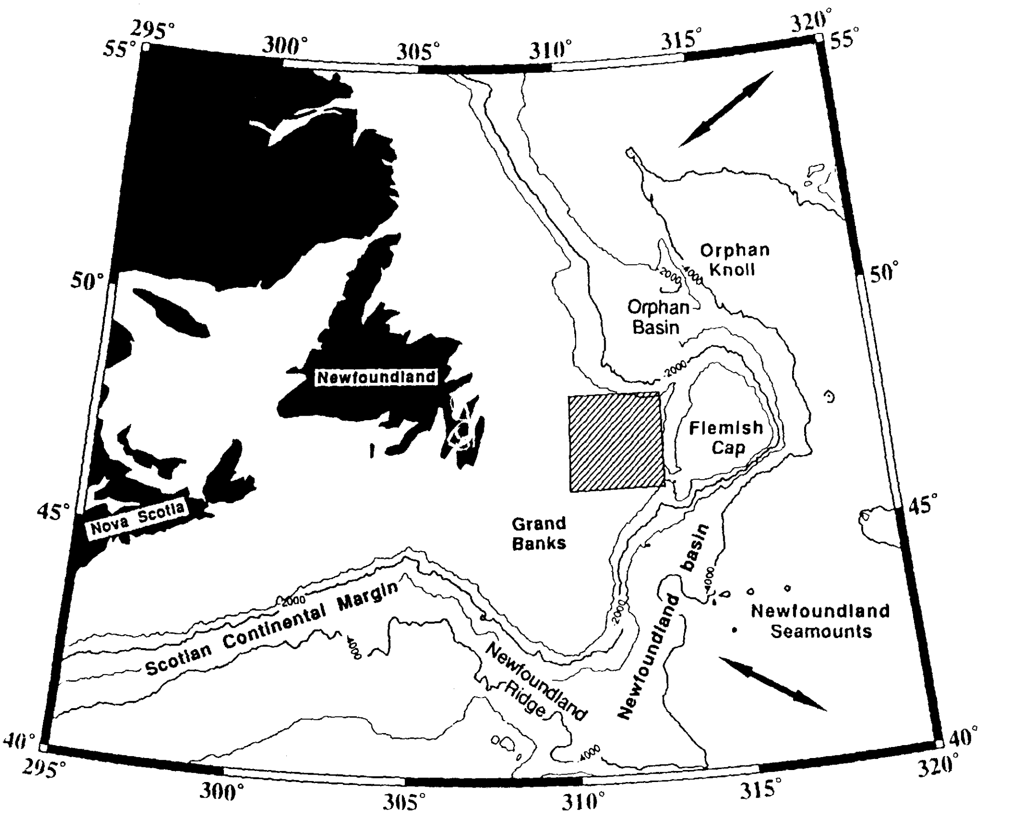


Fig. 1. Location map for the Jeanne d'Arc basin, offshore Newfoundland. The hatchered box denotes the study area. Note the location of Newfoundland Seamounts along the eastern margin of the Grand Banks. The arrows indicate the counterclockwise rotation of the extension direction from northwest–southeast to northeast–southwest from the central Grand Banks to Orphan basin during the Cretaceous.

1989; Tucholke *et al.* 1989; Embry & Dixon, 1990).

One of the primary difficulties with this approach is correctly identifying the break-up unconformity. In some instances, the most prominent unconformity identified along the margin is termed the break-up unconformity, regardless of the associated stratal configuration (Cloetingh *et al.* 1989). The mechanism of unconformity generation is then attributed to either thermal uplift or in-plane force variations resulting from the cessation of rifting and the onset of sea floor spreading (e.g., Falvey 1974; Cloetingh *et al.* 1989; Cathles & Hallam 1991). To avoid ambiguity, we employ the following criteria to identify the break-up unconformity. (1) Bedding within the sedimentary succession beneath the unconformity tends to diverge toward depocentres as a result of differential subsidence due to localized block rotation during rifting. In contrast, the sediments overlying the unconformity typically have greater spatial persistence and more uniform thickness reflecting the regional subsidence associated with the cooling and contraction of the lithosphere (Falvey 1974; Meador & Austin 1988; Embry & Dixon 1990; Karner *et al.* 1993). (2) Growth faults associated with expanded sedimentary sections on the down-thrown block normally occur beneath the unconformity. (3) Faulting and offset should diminish markedly across the break-up unconformity. (4) The subsidence rate generally decreases across the unconformity marking the transition from rift-related to purely thermal subsidence (Hegarty *et al.* 1988; Hiscott *et al.* 1990). (5) Igneous activity tends to be preferentially associated with the sedimentary section beneath the unconformity (Falvey 1974; Enachescu 1987, 1988; Chang *et al.* 1988; Embry & Dixon, 1990).

Using seismic reflection and exploratory well data from the Jeanne d'Arc basin, offshore

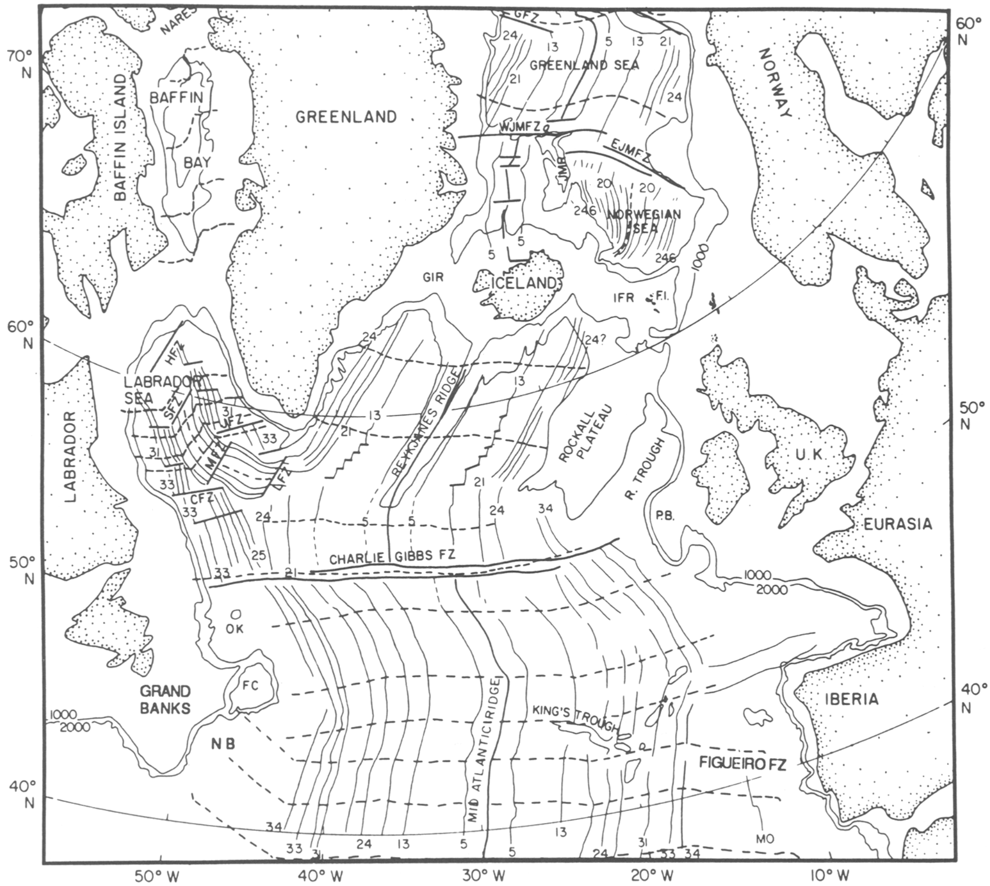


Fig. 2. Map of the northern North Atlantic modified after Srivastava and Tapscott (1986) showing magnetic anomalies along both the Grand Banks and Iberian margins. Note that the location of magnetic anomaly M0 is not shown in the Newfoundland basin on this rendition. Subsequent magnetic studies suggest that anomaly M0 is located near and parallel to the 4000 m contour along the central Grand Banks, shown in Fig. 1. (Abbreviations: NB, Newfoundland basin; FC, Flemish Cap; OK, Orphan Knoll).

Newfoundland (Figs 1 and 2), we assess the link between unconformity generation and the onset of seafloor spreading by determining the temporal and spatial development of the unconformities that appear to be coeval with the onset of seafloor spreading around the Grand Banks region. The main objective of this paper is to investigate the origin of the late Barremian/early Aptian and late Aptian/early Albian unconformities and in so doing, determine if they are actually break-up unconformities as previously interpreted (Srivastava & Tapscott 1986; Keen *et al.* 1987; Tankard & Welsink 1987; Keen & deVoogd 1988; Hubbard 1988; Tankard *et al.* 1989; Cloetingh *et al.* 1989; Tucholke *et al.* 1989; Srivastava *et al.* 1990). In our interpretation, the late Aptian unconformity related to the last phase of rifting is also the break-up unconformity marking the onset of seafloor spreading. The overlying sediments represent the thermal or post-rift subsidence following this last phase of rifting. New interpretation of the magnetic data along the Grand Banks (Enachescu 1988; Cande *et al.* 1989; Srivastava *et al.* 1990) and the conjugate Iberian margin (Whitmarsh *et al.* 1990) suggests that seafloor spreading between the northern portion of the Newfoundland basin and the northern Iberian margin began after the early Aptian. Consequently, we propose that the onset of seafloor spreading in the northern Newfoundland basin was concomitant with the late Aptian cessation of rifting.

Onset of seafloor spreading between the Grand Banks and Iberia

In order to investigate the link between unconformity generation and the onset of seafloor spreading, it was necessary to examine and define the onset of seafloor spreading around the Grand Banks region. The southern margin of the Grand Banks is a transform margin delineated by the Newfoundland fracture zone, which separates the Grand Banks and the Nova Scotian margin (Figs 1 and 2; Enachescu 1988; Todd *et al.* 1988; Verhoef & Srivastava 1989; Welsink *et al.* 1989; Srivastava *et al.* 1990; McAlpine 1991). The Bonnition (Salar) basin, located along the western edge of the Newfoundland basin, and the Orphan basin delineate the eastern and northern boundaries of the Grand Banks, respectively (Figs 1 and 2; Tankard & Welsink 1987; Enachescu 1988; Keen & deVoogd 1988; Austin *et al.* 1989; Tucholke *et al.* 1989; Welsink *et al.* 1989).

On the basis of limited marine magnetic anomaly data, multi-channel seismic reflection data, and DSDP, ODP and exploratory drilling results, it is generally agreed that seafloor spreading began within the Scotian basin south of the Newfoundland fracture zone in the mid-Jurassic (*c.* 175–180 Ma, Bajocian–Bathonian, Haworth & Keen 1979; Royden & Keen 1980; Klitgord & Schouten 1986; Ebinger & Tucholke 1988). The timing of the onset of seafloor spreading between the Grand Banks and Iberia is less firmly established and remains controversial. Mauffret *et al.* (1989) proposed on the basis of marine magnetic data and the existence of landward-dipping crustal reflectors that seafloor spreading between the southern Grand Banks and the southern Iberia margin commenced in the early Tithonian (magnetic anomaly M21). According to Mauffret *et al.* (1989), a subsequent ridge crest jump trapped late Tithonian to early Hauterivian oceanic crust along the portion of the Iberian margin that underlies the sediments of the Tagus Abyssal Plain.

In contrast, between the Grand Banks (bounded by the Newfoundland Ridge to the south and Flemish Cap to the north; Figs 1 and 2) and Iberia, it has been proposed by Srivastava & Tapscott (1986), Keen & deVoogd (1988), Klitgord *et al.* (1988), and Verhoef & Srivastava (1989), that seafloor spreading began in the late Neocomian (*c.* 125 Ma, late Hauterivian). Nevertheless, the oldest identified magnetic anomaly in the Newfoundland basin east of the Grand Banks is magnetic anomaly M0 (Fig. 1; Meador *et al.* 1988; Austin *et al.* 1989; Cande *et al.* 1989; Tucholke *et al.* 1989; Verhoef & Srivastava 1989). Therefore, on the basis of magnetic, seismic reflection, and refraction data, it has been proposed that seafloor spreading between the central Grand Banks and Iberia commenced at magnetic anomaly M0 time (*c.* 118 Ma, early Aptian; Enachescu 1988; Meador *et al.* 1988; Austin *et al.* 1989; Tucholke *et al.* 1989). Recent studies indicate that magnetic anomaly M0 might not continue north to the Flemish Cap as previously proposed, but terminates in the vicinity of the Newfoundland Seamounts (Fig. 1; Enachescu 1988; Srivastava *et al.* 1990). Along the conjugate Iberian margin magnetic anomaly M0 is not observed north of the Figueiro fracture zone (Whitmarsh *et al.* 1990) indicating that the onset of seafloor spreading in this region occurred after the early Aptian (Fig. 2; Enachescu 1988; Srivastava *et al.* 1990; Whitmarsh *et al.* 1990). Farther north, between Flemish Cap and Goban Spur, spreading began by at least late Albian time (Montadert *et al.* 1979; Tankard *et al.* 1989; Ziegler 1989; Whitmarsh *et al.* 1990). Seafloor spreading between Orphan Knoll and Porcupine Bank commenced at or before magnetic anomaly 34 during Santonian time (*c.* 84 Ma, Verhoef & Srivastava 1989; Ziegler 1989; Srivastava *et al.* 1990).

As extension propagated from the central North Atlantic northward around the Grand Banks, its orientation appears to have rotated from WNW (late Barremian/early Aptian) to WSW (late Albian/early Cenomanian) (Figs 1 and 2; Keen & deVoogd 1988; Tankard *et al.* 1989; Verhoef & Srivastava, 1989; Welsink *et al.* 1989). The counter-clockwise rotation of the seafloor spreading direction during the Cretaceous is consistent with palaeostress patterns inferred from igneous dyke swarms (McHone, 1988). Therefore, our seismic sequence analysis has focused on the upper Barremian to base Tertiary stratigraphy in the Jeanne d'Arc basin to determine the tectonic and stratigraphic response of the basin to the northward propagation of seafloor spreading and the counter-clockwise rotation of the inferred regional stress field.

Geological setting of the Jeanne d'Arc basin

The geometry and distribution of rift basins across the Grand Banks are controlled primarily by the Mesozoic reactivation of the pre-existing fabrics in the Avalon and Meguma terranes (Haworth & Keen 1979; Hubbard *et al.* 1985; Tankard and Welsink, 1987; Enachescu 1988). The Jeanne d'Arc basin is the largest rift basin in

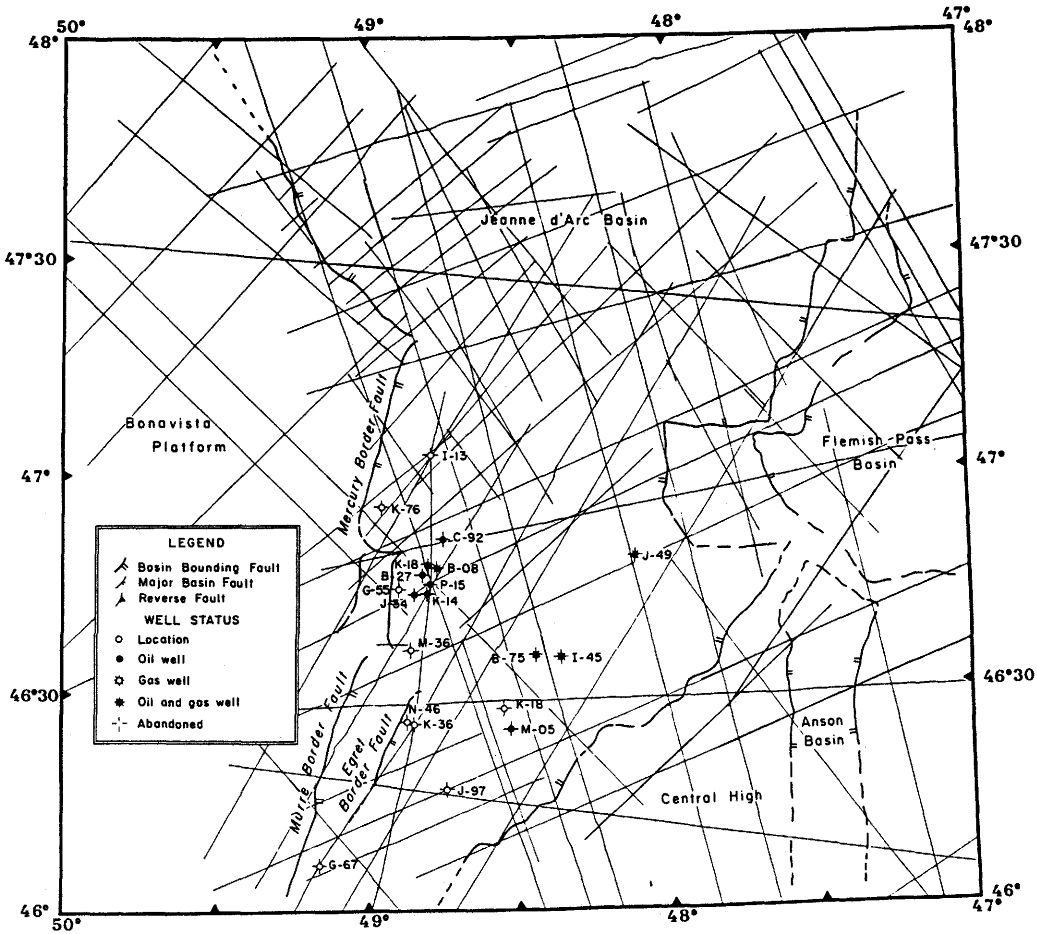


Fig. 3. Portion of the Grand Banks relevant to this study showing the Jeanne d'Arc, Anson, and Flemish Pass basins. The multi-channel seismic reflection and exploratory well data used in this study are shown.

the Grand Banks region, containing approximately 14 km of syn-rift sediment (Keen *et al.* 1987; Tankard & Welsink 1987). The Murre and Mercury curvilinear border faults separate the southern and central portions of the Jeanne d'Arc basin from the Bonavista platform to the west, respectively (Figs 3 and 4). The border faults trend approximately NNE. Interpretation of seismic refraction data indicates that the continental crust beneath the Bonavista platform is approximately 35 km thick and thins eastward tto about 15 km beneath the Flemish Pass and Orphan basins (Fig. 3; Keen & Barrett 1981; Tankard & Welsink 1987). Hanging-wall monoclines and antithetic faults delineate the eastern boundary between the 'funnel-shaped' Jeanne d'Arc basin and the relatively unextended Central High (Figs 3 and 4).

The stratigraphic succession preserved in the Jeanne d'Arc basin records the complex interplay between tectonics and eustasy that affected the space available to deposit sediments across the Grand Banks region (Fig. 5; Jansa & Wade 1975; Hubbard *et al.* 1985; Tankard & Welsink 1987; Grant *et al.* 1988; Tankard *et al.* 1989; Tucholke *et al.* 1989; McAlpine, 1991). The Jeanne d'Arc basin was established in the late Triassic. Earliest deposits are fluvial to lacustrine sediments (Eurydice Formation; Jansa & Wade 1975; Enachescu 1987, 1988; Tankard *et al.* 1989; McAlpine, 1991). Repeated marine incursions into the rift systems from the Tethys Sea led to the development of widespread evaporite deposits in the basin (Argo Formation) that overly the Eurydice Formation (Tucholke *et al.* 1989; McAlpine 1991). Regional

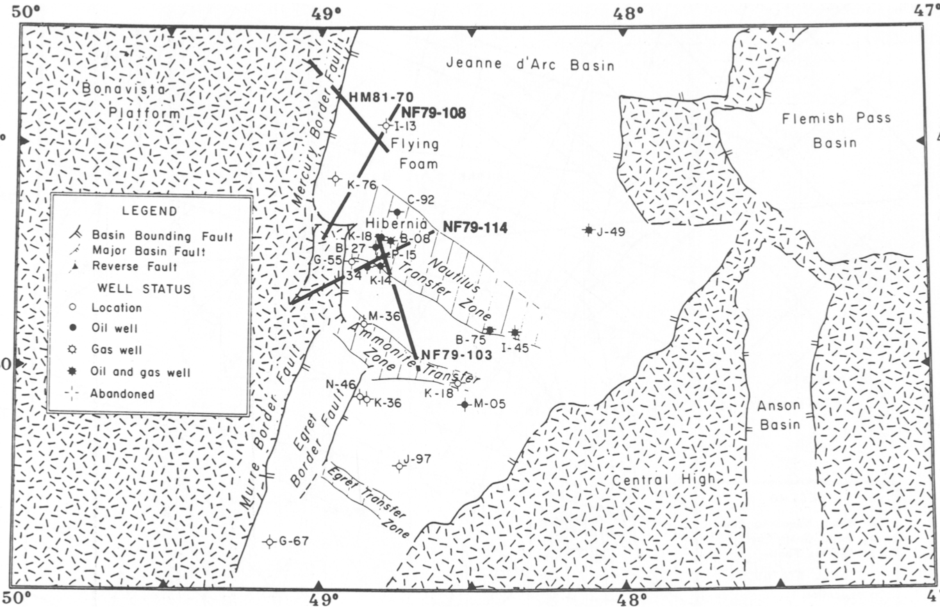


Fig. 4. A generalized structure map illustrating the relationship between the transbasinal fault zones (transfer zones) and the Murre and Mercury border faults. From south to north, the transfer zones are referred to in the text as Egret, Ammonite, and Nautilus. The fault displacement and the relief of the intrabasinal highs associated with the transfer zones diminish basinward. Bold lines show the location of the multi-channel seismic reflection shown in Figs 6, 7, 8, and 10.

thermal subsidence of the Grand Banks region following the late Triassic to early Jurassic rifting episode created space for the deposition of marine sandstone, shales, and carbonates (Tankard & Welsink 1987; Grant *et al.* 1988; McAlpine 1991). The Jeanne d'Arc Formation, a coarse-grained sandstone to conglomeratic braided-fluvial deposit overlying the carbonates of the Rankin Formation, has been interpreted to record another rifting episode that affected the Grand Banks in the late Jurassic (Tankard & Welsink 1987; Grant *et al.* 1988; Tankard *et al.* 1989; McAlpine 1991). During the late Jurassic/early Cretaceous, basin infilling by clastic sediments (Whiterose and Hibernia formations) with the occasional interspersed carbonate stringer (Fig. 5; e.g., B marker, Valanginian) kept pace with the overall thermal subsidence (Hubbard *et al.* 1985; Welsink & Tankard 1988).

New interpretations of seismic reflection and exploratory well data suggest that extensional deformation within the Jeanne d'Arc basin north of the Egret transfer zone continued until at least late Aptian/early Albian time resulting in the generation of the late Barremian/early Aptian and late Aptian/early Albian unconformities above which were deposited the Avalon and Ben Nevis formations, respectively (Fig. 5; Driscoll *et al.* 1990; Driscoll 1992; Karner *et al.* 1993; Driscoll & Hogg 1995). The unconformity underlying the Avalon Formation has been interpreted to be of middle Barremian to late Barremian/early Aptian age on the basis of our recent biostratigraphic studies of the palynomorph assemblages using both cores and well cuttings. For the sake of simplicity, we here use the late Barremian age when referring to this unconformity. In a similar fashion, we use the term late Aptian when referring to the unconformity beneath the Ben Nevis Formation.

Structure and stratigraphy

Multi-channel seismic reflection data were used to map the regional and local structure of the Jeanne d'Arc basin in order to assess the influence of the pre-existing border fault/transfer fault geometry on the late Barremian to base Tertiary stratigraphy (Fig. 3). Five major seismic sequence boundaries were identified within the

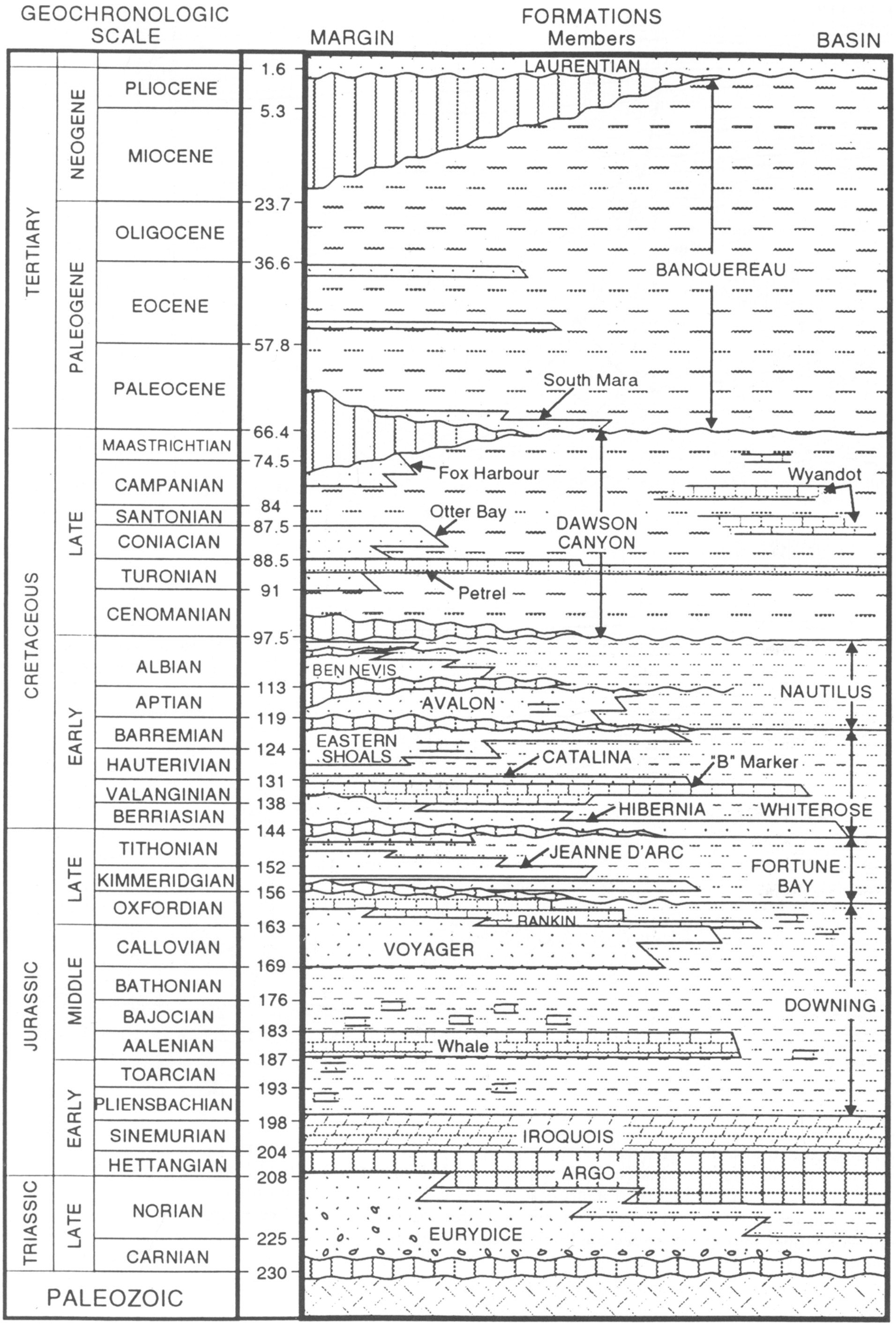


Fig. 5. Generalized lithology and lithostratigraphy for the Jeanne d'Arc basin. Note the relationship between the late Barremian, late Aptian, and late Albian unconformities and the lithostratigraphy (modified from McAlpine 1991).

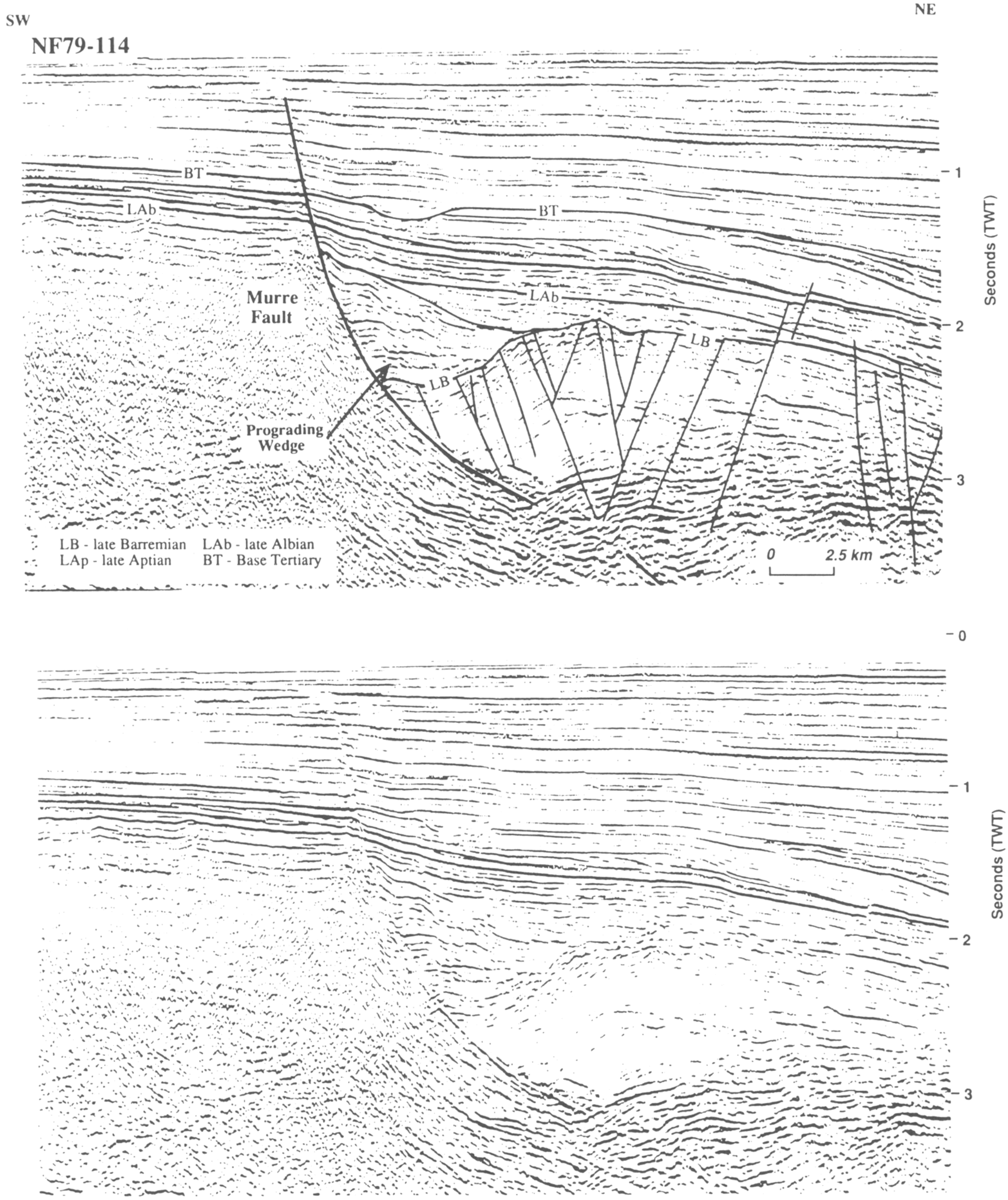


Fig. 6. Interpreted and uninterpreted seismic reflection profile NF79-114 illustrating the collapsed hanging-wall deformation due to late Barremian extension across the Murre border fault. The reflectors that downlap onto the late Barremian unconformity form a prograding wedge geometry that correlates with locally-derived upper Barremian–lower Aptian sandstones. The overlying reflectors that onlap the prograding wedge correlate with marine sandstones that are more regionally persistent throughout the basin. Location of seismic profile is shown in Fig. 4.

Jeanne d'Arc basin by applying the technique of seismic sequence stratigraphy (Vail 1987). Sequence stratigraphy is the study of repetitive, genetically related strata bounded by unconformities and their correlative conformities within a time-stratigraphic framework (Vail 1987; Van Wagoner *et al.* 1988; Christie-Blick & Driscoll 1995). Sequence stratigraphic concepts may be applied to predict depositional environments from the stratal patterns and acoustic character observed in seismic reflection data. Isopach maps were generated to analyse the spatial variations of the stratigraphic sequences. Multichannel stacking velocities and velocity information derived from exploratory well data were used to convert two-way travel time into sediment thickness. The depositional palaeoenvironments were estimated by correlating the seismic reflection data to the exploratory well data. The chronostratigraphy used in this study is based primarily on palynology and, where available, augmented by microfossil zonations (foraminifera). We used the Kent & Gradstein (1985) DNAG time-scale. The formations proposed by Grant *et al.* (1988) and McAlpine (1991) for the Jeanne d'Arc basin are identified on the basis of lithic characteristics and position within the stratigraphic succession and are not necessarily time-stratigraphic units. The time-stratigraphic sequences in the Jeanne d'Arc basin referred to in this paper were identified by seismic sequence stratigraphy and palynology.

The Murre and Mercury border faults strike primarily NNE and are segmented by transfer zones (Fig. 4). The transfer zones are highly-faulted regions that form intra-basinal highs. We propose that the formation of these intrabasinal highs is a direct consequence of differential displacement on segmented border faults and the collapse of the hanging-wall block in three dimensions (Driscoll & Hogg 1995). West-northwest extension across the Grand Banks reactivated the Murre and Mercury border faults in a normal sense during late Barremian, early Aptian, and late Aptian time (Driscoll 1992; Driscoll & Hogg 1995). The structural and stratigraphic response of the Jeanne d'Arc basin to these extensional events is illustrated using seismic reflection dip lines across the border faults (Figs 6–8). The location of these seismic reflection profiles is shown in Fig. 4.

Seismic reflection profile NF79-114 (Fig. 6) crossing the Murre border fault illustrates hanging-wall collapse in response to the late Barremian extensional event. The internal deformation of the hanging wall is accommodated by a complex pattern of synthetic and antithetic faults (Fig. 6). The observed horizontal component of displacement across the border fault, therefore, does not reflect the actual extension between the hanging wall and footwall (e.g., White *et al.* 1986). Consequently, caution should be employed when using the displacement of the hanging wall with respect to the footwall across a fault as a proxy to estimate the amount of extension. A thick wedge of sediment is developed along the fault and thins basinward by downlap onto the pre-existing strata. Exploratory well Hibernia G-55 is located on the northern edge of this depocentre and sampled thick accumulations of coarse-grained clastic sediments (*c.* 1000 m; Fig. 4). High-angle cross-stratification, and pebble lags observed within the cored interval of G-55 (*c.* 2243.2–2453.9 m below the Kelly Bushing, KB) are interpreted to be indicative of fluvial or fan-delta sedimentation. The cored section from Hibernia G-55 shows no evidence of bioturbation, but it is uncertain whether the sediments accumulated in a subaerial or subaqueous environment. The subdued rift flank topography near the intersection of the Murre border fault and the Ammonite transfer zone might have allowed the fluvial drainage system access to the basin (Fig. 4). The geometry and location of this sedimentary wedge along the Murre border fault suggests that it is a fan delta (e.g., Leeder & Gawthorpe, 1987; McPherson *et al.* 1987). The overlying late Barremian/early Aptian sediments, which can be traced more regionally throughout the basin, onlap against the locally-developed sedimentary wedge (Fig. 6). Palynomorphs and sedimentary structures observed within the exploratory cores indicate that the more regionally deposited sediments are marine and were deposited in a middle to lower shoreface (Driscoll & Hogg 1995).

The onlap surface observed in the seismic reflection profile separates regionally-derived sandstones above (e.g., Hibernia P-15) from the locally-derived sandstones that comprise the prograding wedge below (e.g., Hibernia G-55; Fig. 4). Many rift basins display a similar two-stage stratigraphic response to extension: a local response restricted by the local basin architecture (i.e., border/transfer fault interaction), and a more regional response governed by the larger border fault offsets of the rift system and existing drainage networks (Leeder & Gawthorpe 1987; Frostick & Reid 1989; Morley *et al.* 1990; Lambiase 1991; Driscoll 1992; Driscoll & Hogg 1995).

Farther north across the Nautilus transfer zone, the Flying Foam structure parallels the Mercury border fault and thus isolates the Mercury sub-basin from the rift basin proper (Fig. 4). The Flying Foam structure appears to be a rider block of Avalon terrane overlying the Mercury border fault. The faults associated with the rotation and internal deformation of this rider block are also oriented roughly parallel to the Mercury border fault. Experimental sand models of hanging-wall deformation with a

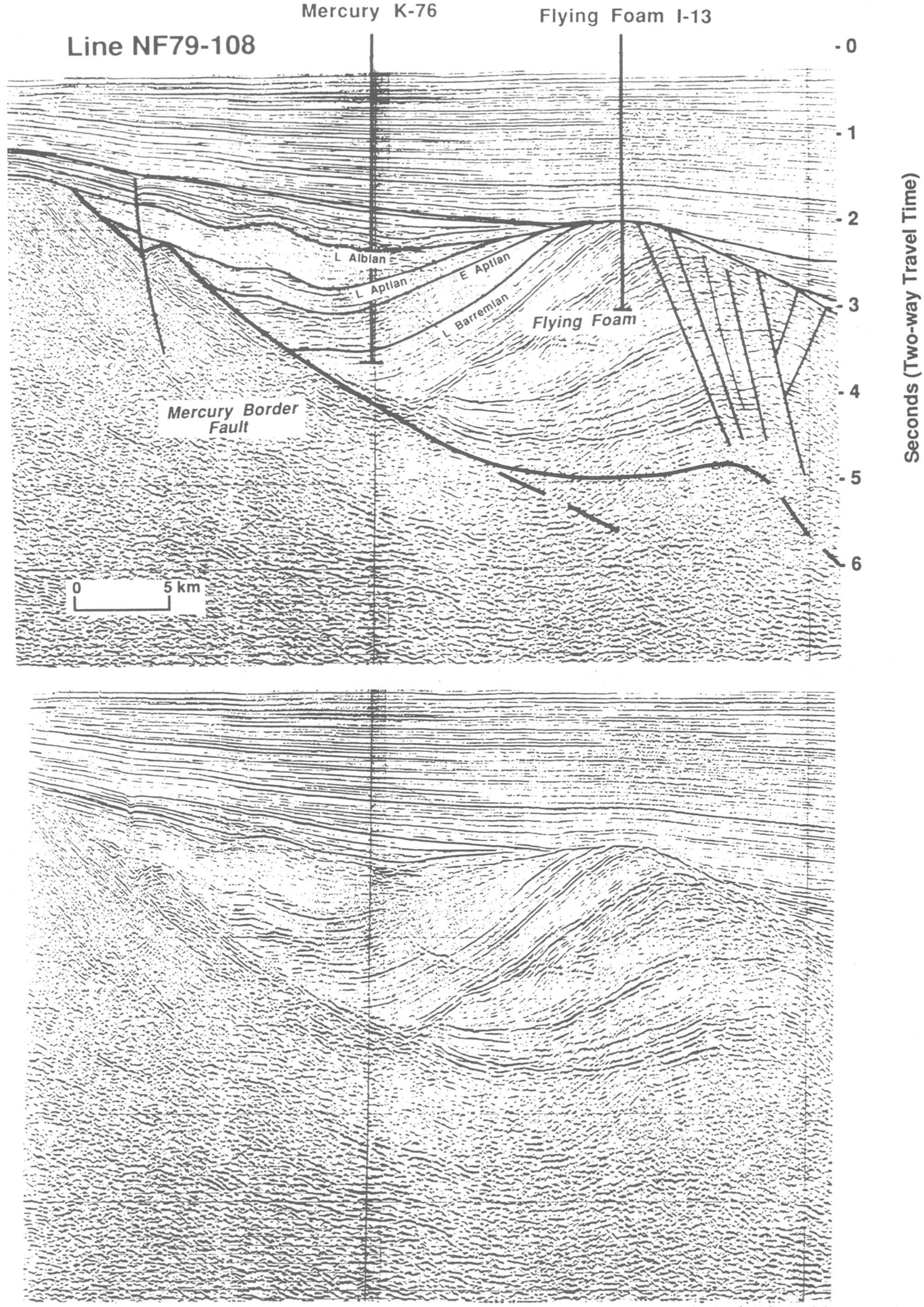


Fig. 7. Interpreted and uninterpreted seismic reflection profile (NF79-108) that crosses the curvilinear portion of the Mercury border fault and the Flying Foam structure. The divergence and rotation of the seismic reflectors indicate three episodes of differential subsidence beginning in the late Barremian and culminating in the late Aptian. Note the upper Aptian to upper Albian sediments are flat-lying with minimal evidence suggesting divergence. The location and penetration of exploratory well Flying Foam I-13 is projected onto the seismic reflection profile. Location of seismic profile is shown in Fig. 4.

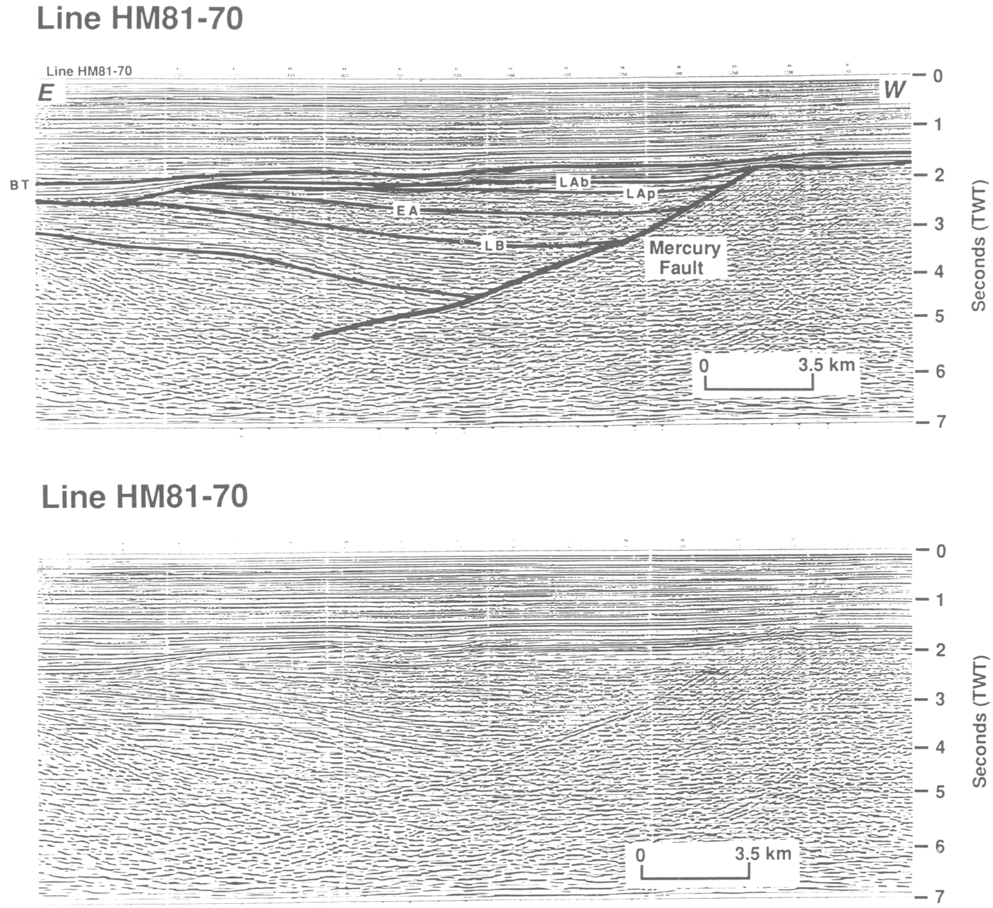


Fig. 8. Interpreted and uninterpreted seismic reflection profile (HM81-70) that crosses the Mercury fault and sub-basin. Extensional reactivation of the Mercury border fault occurred during the late Barremian, early Aptian, and late Aptian as evidenced by the divergent and onlapping seismic reflectors. The sequences that onlap the border fault show no indications of the late Albian reactivation. (Abbreviations: LB, late Barremian unconformity; EA, early Aptian unconformity, LAp, late Aptian unconformity; LAb, late Albian unconformity, and BT, Base Tertiary unconformity).

listric ramp-flat geometry produce similar deformational features during extension (Tankard *et al.* 1989; McClay & Scott 1991). Seismic reflection line 79-108 traverses this structure obliquely (Fig. 4), and thus crosses the Mercury border fault where the fault curves toward the Nautilus transfer zone. The seismic reflectors underlying the late Barremian unconformity appear parallel and are roughly concordant with the underlying Kimmeridgian unconformity (Tankard *et al.* 1989). The overlying seismic reflectors onlap onto the top of the parallel, concordant reflectors (Fig. 7). The dip of the onlapping seismic reflectors diminishes upsection and is indicative of differential subsidence and block rotation (Fig. 7). Note that the divergent reflectors onlap onto a single surface, indicating that the increase in accommodation outpaced the input of sediment. Each phase of differential subsidence is recorded by a divergent stratigraphic package. Eustatic variations alone cannot explain the divergence and rotation of these stratigraphic packages. Consequently, we propose that the late Barremian, early Aptian, and late Aptian unconformities document episodes of active block rotation, and are therefore rift-onset unconformities. Conversely, reflectors in the upper Aptian to upper Albian interval are parallel with minimal signs of rotation suggesting that extensional deformation had ceased by late Aptian time. Minor deformation of the upper Barremian to upper Albian section is observed near the curved portion of the Mercury border fault. The small undulations (folds) observed in the seismic section (Fig. 7) are associated with the late Albian deformation (see below).

Seismic reflection line HM81-70 also images the thick upper Barremian to upper Albian sediment preserved in the basin (Fig. 8). The divergence and onlap of seismic reflectors overlying the late Barremian, early Aptian, and late Aptian unconformities attest to an increase in accommodation at these times (Figs 7 and 8). The thickness of these sequences progressively decreases eastward away from the basin depocentre.

Now we present a simple schematic (Fig. 9) to illustrate how the seismic reflectors can be used to infer the deformational history of a basin. Parallel reflectors (Fig. 9a) are indicative of uniform subsidence across a basin and are interpreted as the regional thermal subsidence of an earlier extensional event. In the case of the Jeanne d'Arc basin, this thermal subsidence phase is likely a consequence of the late Jurassic to early Cretaceous rifting episode (Tankard & Welsink 1987; Grant *et al.* 1988; McAlpine 1991). Divergence and rotation of seismic reflectors is indicative of differential subsidence and block rotation (Fig. 9b). Note that the divergent reflectors resulting from a phase of differential subsidence onlap onto a single surface (Fig. 9b). Each phase of differential subsidence is recorded by an onlapping stratigraphic package (Fig. 9c).

In contrast to the increase of accommodation recorded by the divergent and rotated reflectors seen in Figs 6–9, the late Aptian to late Albian seismic reflectors overlying the Hibernia structure (Fig. 10) record a decrease or reduction of accommodation. Specifically, the seismic reflectors overlying the late Aptian unconformity do not onlap the Hibernia structural high (Fig. 10). The seismic reflectors do, however, onlap the structural high to the southeast. Thus, the uplift of the Hibernia structure must have occurred after the deposition of the upper Aptian to upper Albian sediments. The Hibernia structure is a consequence of reactivation of the transfer faults in a reverse sense. The reactivation uplifted the same crustal blocks that were involved in earlier extensional events. Erosional truncation registering this uplift is best developed along the intersection between the transfer zones and border faults. Given the observed stratal geometry (i.e., truncation and onlap; Fig. 10), the minimum amplitude of the relative topography due to the brittle deformation is 250 m.

From the distribution of the deformational

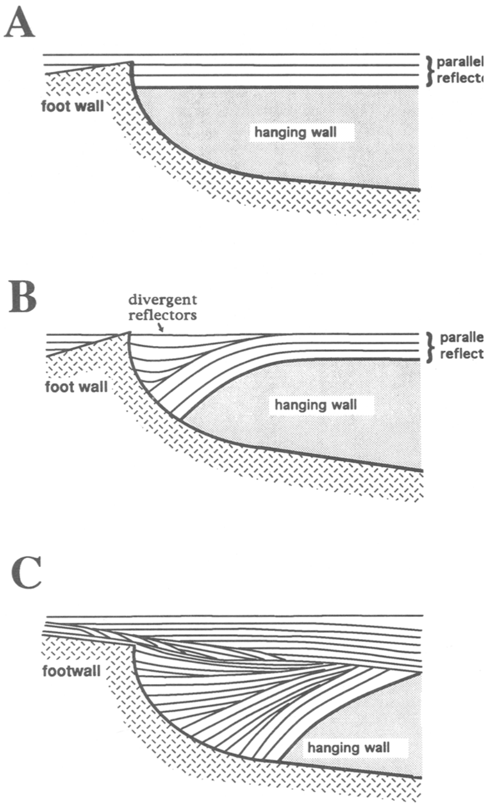
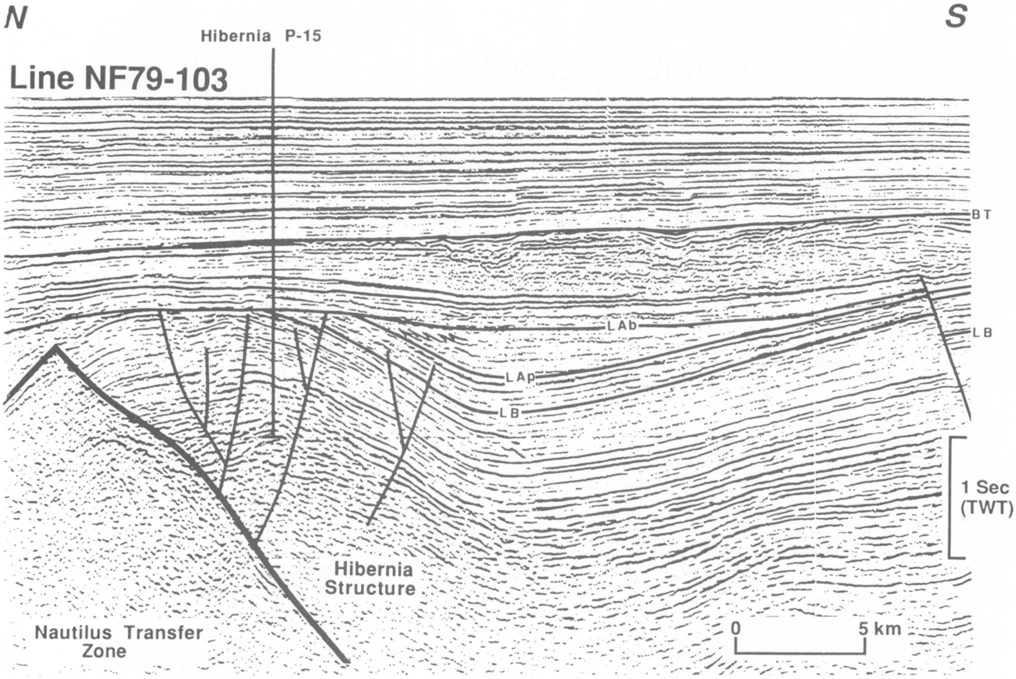


Fig. 9. A simple schematic illustrating the divergence and rotation of the sediments in an extensional setting due to differential subsidence (block rotation). **(A)** Parallel reflectors are indicative of regional uniform subsidence interpreted to be due to thermal subsidence across the basin. **(B)** Divergence and rotation of seismic reflectors, indicating differential subsidence and block rotation. **(C)** Final stratal geometry of the basin demonstrating three rifting episodes characterized by stratigraphic packages bounded by unconformities. Post-rift prograding and onlapping stratigraphic packages subsequently fill the basin.

structures, it is possible to define the trajectory of the in-plane force responsible for the late Albian unconformity. For example, the structures associated with the late Albian reactivation are observed only across the transfer zones (Fig. 10). Seismic reflection profiles crossing the border faults (e.g., Figs 6 and 8) do not show any evidence of reactivation structures. Therefore, the orientation of the late Albian compression was NNE parallel to the Jeanne d'Arc basin. The Hibernia structure is a direct result of



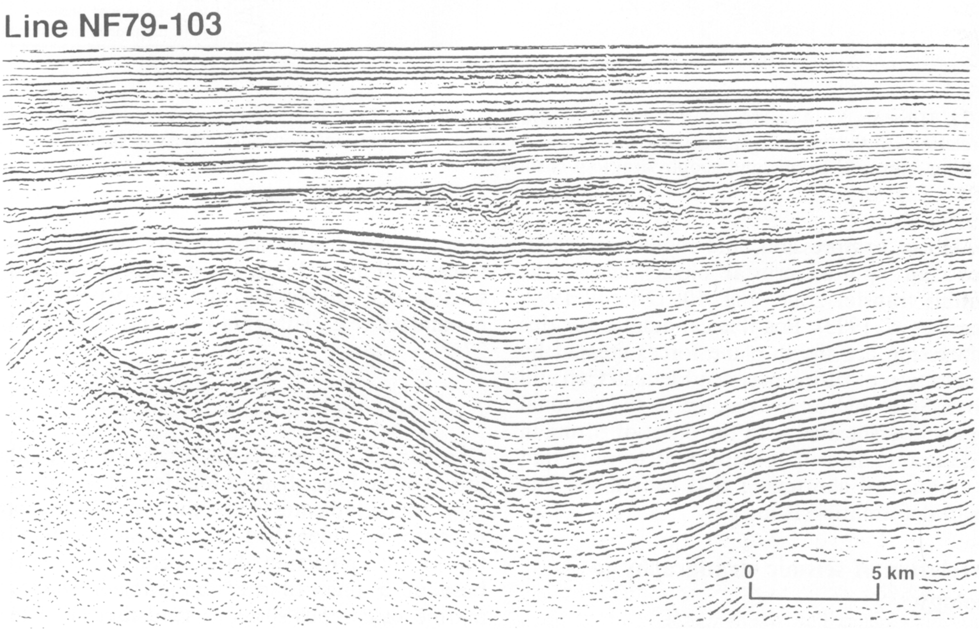


Fig. 10. Interpreted and uninterpreted multi-channel seismic reflection profile across the Jeanne d'Arc basin (NF79-103). The profile crosses both the Nautilus transfer zone and the Ammonite transfer zone. The triangular ridge of unextended Avalon terrane (i.e., Nautilus transfer zone) extends into the basin due to the interaction of the two border faults (e.g., relay ramp). Re-activation of the Nautilus transfer zone by north-northeast in-plane compression uplifted and deformed the Hibernia structure in the late Albian. Note the seismic reflectors overlying the late Aptian unconformity onlap the structural high towards the southeast, but do not onlap onto the Hibernia structure. In fact, the reflectors overlying the Hibernia structure are truncated. (Abbreviations: LB, late Barremian unconformity; LAp, late Aptian unconformity; LAb, late Albian unconformity; BT, Base Tertiary unconformity)

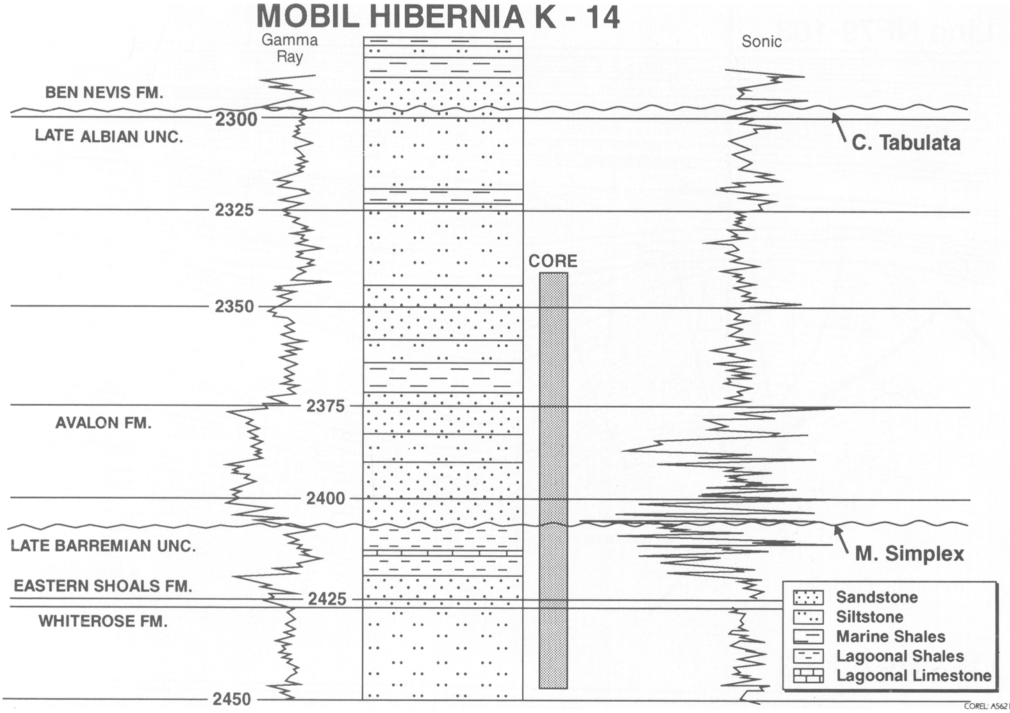


Fig. 11. Hibernia K-14 well is located just to the south of Hibernia P-15. See Figs 3 and 4 for exact location. Correlation of the unconformities determined on the basis of stratal relationships observed in the seismic reflection data to lithology and geophysical logs is shown.

late Albian compression, and represents reactivated and uplifted crustal blocks across the Nautilus transfer zone (Fig. 10; Driscoll 1992; Karner *et al.* 1993). Possible candidates for this compression are the in-plane forces created by the cessation of rifting between Flemish Cap and Goban Spur and/or the change in the regional stress field associated with the onset of rifting in the Labrador Sea. It is important to note that the amount of shortening that caused the late Albian deformation is minor.

Correlation of seismic stratigraphy to lithology

Downhole acoustic impedance contrasts were calculated using velocity and density data recorded at a 0.5 m sampling interval from the exploratory wells. A series of filtered synthetic seismograms, generated by convolving a zero phase wavelet with the downhole acoustic impedance contrasts, allowed the lithology to be correlated to the seismic stratigraphy. The majority of wells in the Jeanne d'Arc basin were located to exploit structural traps (i.e., culminations), and in so doing, the missing sedimentary section due to erosion and non-deposition is maximized (e.g., Hibernia P-15 and Hibernia B-27).

Late Barremian unconformity

Correlation of the seismic stratigraphy to the lithology and geophysical logs from the exploratory wells indicates that the late Barremian unconformity identified on the basis of onlap in the seismic reflection data correlates with the base of a fine- to medium-grained, shallow-marine, calcareous/siliceous sandstone (Fig. 11). The base of this sandstone correlates with a sharp decrease upwards in natural radioactivity recorded in the gamma ray log. The low natural radioactivity signature on the gamma ray log is consistent with our interpretation that these sandstones are indicative of a winnowed shoreface depositional environment. The sandstones gradually become finer-grained upsection and pass into glauconitic siltstones. This trend is

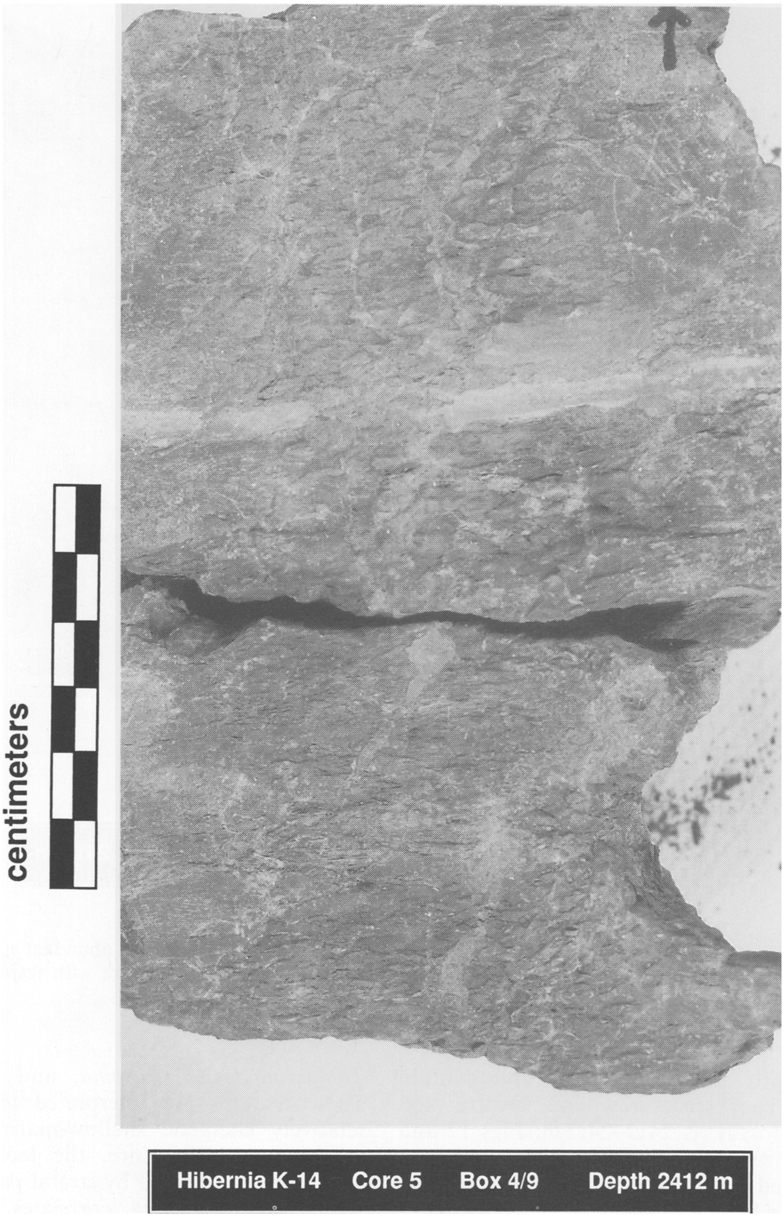


Fig. 12. A cored interval from Hibernia K-14 recovered iron-stained shales beneath the late Barremian unconformity. See Fig. 11 for location of core with respect to the late Barremian unconformity.

reflected in the gamma ray log values as the natural radioactivity increases up section. In addition to fining-upward, the sandstones also become gradually finer-grained away from the border faults toward the basin depocentre.

The cored interval (*c.* 2345–2439 m beneath KB) at Hibernia K-14 permitted a detailed examination of the preserved lithology and sedimentary structures below and above the late Barremian unconformity (Figs 12–14). Carbonaceous shales immediately beneath the unconformity are dark grey to black as well as iron-

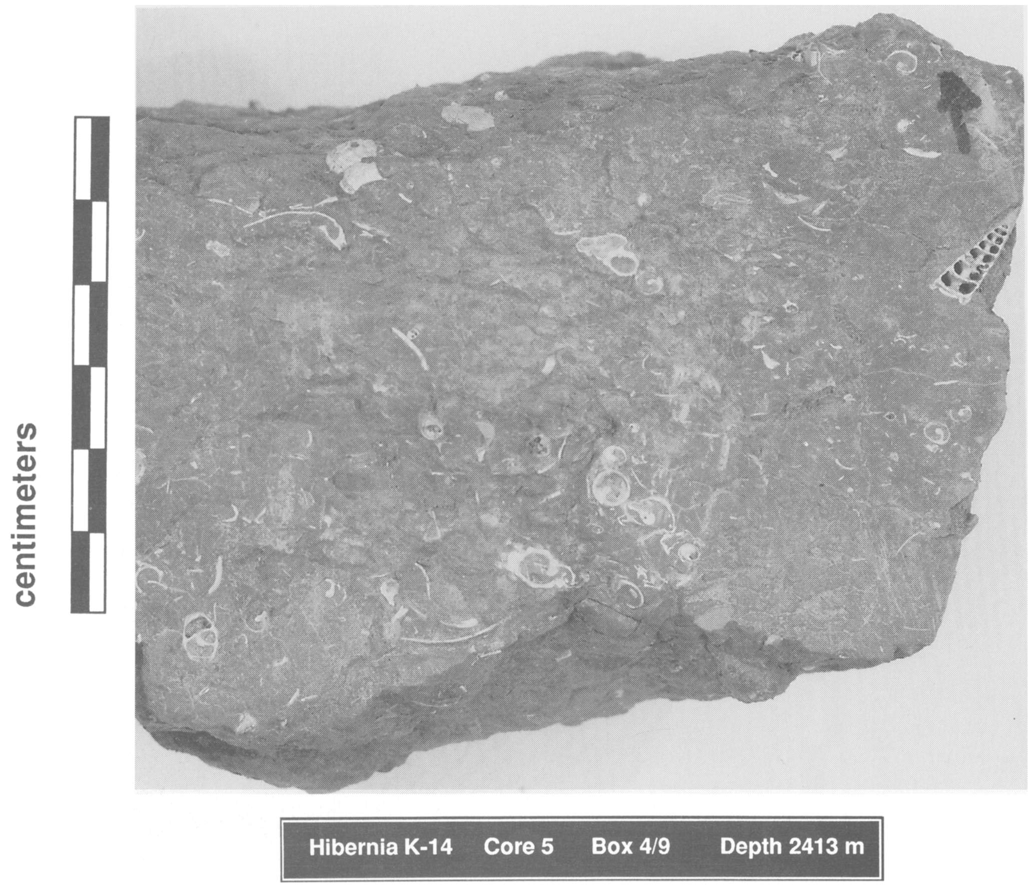


Fig. 13. A cored interval from Hibernia K-14 recovered dark to grey shales with abundant gastropods and bivalves beneath the late Barremian unconformity. See Fig. 11 for location of core with respect to the late Barremian unconformity.

stained, with sideritic nodules and contain abundant root structures, and bivalve and gastropod fossils (*c.* 2412–2413 m; Figs 12 and 13). These iron-stained, carbonaceous shales are characterized by low-velocity zones in the sonic logs and can be easily correlated across the basin (Fig. 11; McAlpine 1991). These observations, together with palynomorph data, are taken to indicate a non-marine and lagoonal to restricted marine depositional environment. In contrast, sandstones overlying the unconformity are massive to low-angle cross-stratified (possibly with hummocky cross-stratification; Fig. 14). Bio-turbation is relatively common and for the most part restricted to the *Skolithos* ichnofacies (for example: *Ophiomorphia*, *Diplocraterion*, and *Skolithos*, with minor occurrences of *Thalassinoides*, *Astrosoma*, and *Zoophycos*). These features are interpreted to indicate a relatively energetic shallow-marine shoreface environment. Therefore, the late Barremian unconformity, defined by stratal patterns in the seismic reflection data, correlates to a marine onlap surface that records an increase in accommodation across the unconformity.

Late Aptian unconformity

The late Albian erosional truncation along and across the western portions of the transfer zones diminishes eastward, and thus minimizes the hiatus associated with the unconformity. The more continuous stratigraphic section within the basin permitted correlation of the additional

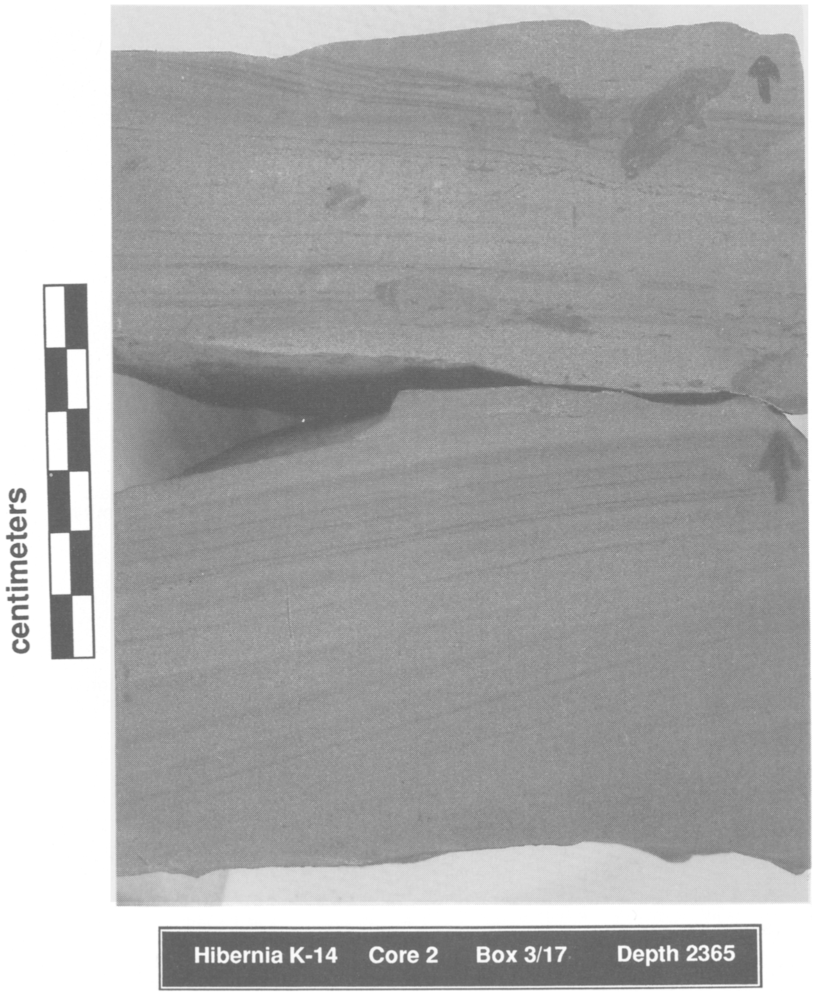


Fig. 14. A cored interval from Hibernia K-14 recovered sandstone units above the late Barremian unconformity. Sedimentological, ichnological, and palynological evidence suggests that the sandstones were deposited in an open marine to restricted marine environment. See Fig. 11 for location of core with respect to the late Barremian unconformity.

unconformities identified on the basis of reflector geometry observed in the seismic reflection data to the sampled lithology. Terra Nova well K-18 is located along the eastern portion of the Ammonite transfer (Figs 3 and 4). At this well, the late Barremian unconformity is overlain by a lower Aptian blocky glauconitic sandstone (*c.* 1790 m beneath KB; Fig. 15). Continuing upsection the grain size diminishes and the sandstones grade into siltstones and shales with a concomitant increase in shell fragments (Fig. 15). The late Aptian unconformity correlates (*c.* 1710 m beneath KB) with an abrupt facies change from calcareous shale to sandstone (Fig. 15). The lower to upper Albian interval overlying the late Aptian unconformity consists of fine- to very fine-grained calcite-cemented, glauconitic sandstones with thin interbeds of sandy, fossiliferous limestones (Fig. 15). The Albian sequence (*c.* 1550–1710 m beneath KB) displays an overall fining-upward trend, from fine-grained sandstones at the base through bioturbated, glauconitic siltstones in the middle to glauconitic shales toward the top (Fig. 15). Examination of cores recovered from the West Ben Nevis B-75 well, located 15 km NNE of

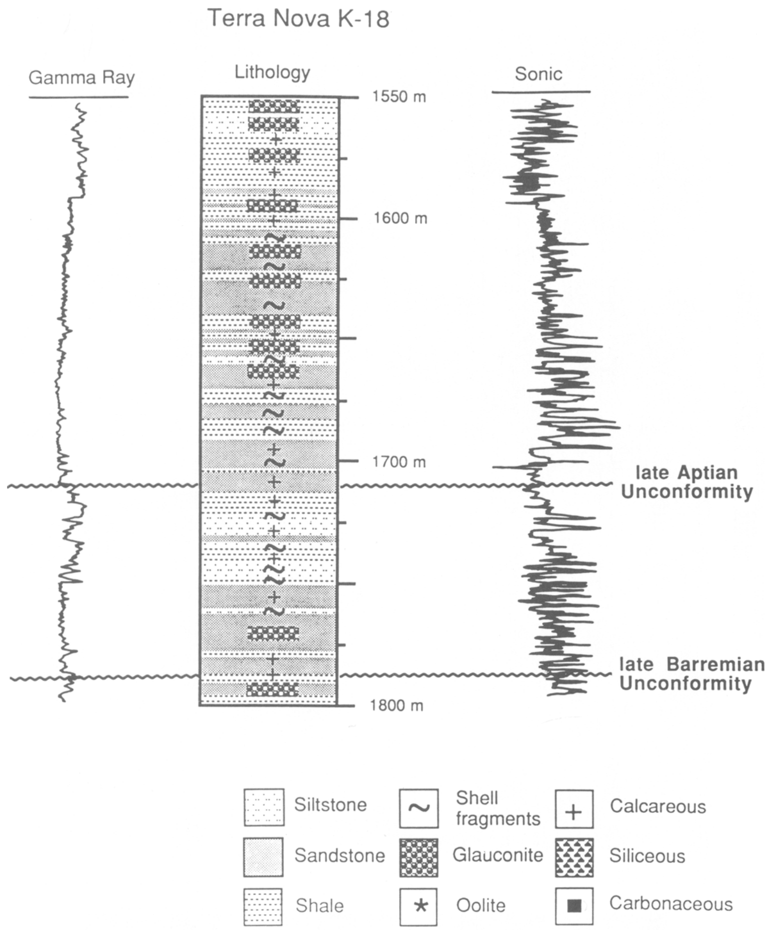


Fig. 15. Exploratory well Terra Nova K-18 is located along the eastern portion Ammonite transfer zone. See Figs 3 and 4 for exact location. Correlation of the unconformities determined on the basis of stratal relationships observed in the seismic reflection data to lithology and geophysical logs is shown. Note the thick sandstone overlying the late Aptian unconformity.

Terra Nova K-18 (Figs 3 and 4), suggests that the sandstones were deposited in a shallow shelf environment during early Albian time with open to restricted marine conditions. The cored interval (*c.* 2004–2095 m beneath KB) consists of bioturbated sandstones with interbedded shell debris (pelecypods, gastropods, and serpulid worm tubes). The bioclastic layers are interpreted to represent storm events. Ichnological studies of the West Ben Nevis B-75 core indicate that the bioturbation is predominantly in the *Skolithos* ichnofacies at the base of the Albian sequence and shifts to the *Cruziana* ichnofacies toward the top of the sequence (primarily: *Ophiomorphia*, *Planolities* and *Teichichnus*). The transition from *Skolithos* to *Cruziana* ichnofacies implies an overall increase in palaeowater depth (Pemberton *et al.* 1984), which is consistent with the observed upward fining trend, a feature that is characteristic of the Albian sequence sampled throughout the Jeanne d'Arc basin.

Late Albian unconformity

The late Albian unconformity identified on the basis of reflector geometry at Hibernia P-15 correlates with an abrupt upward facies change

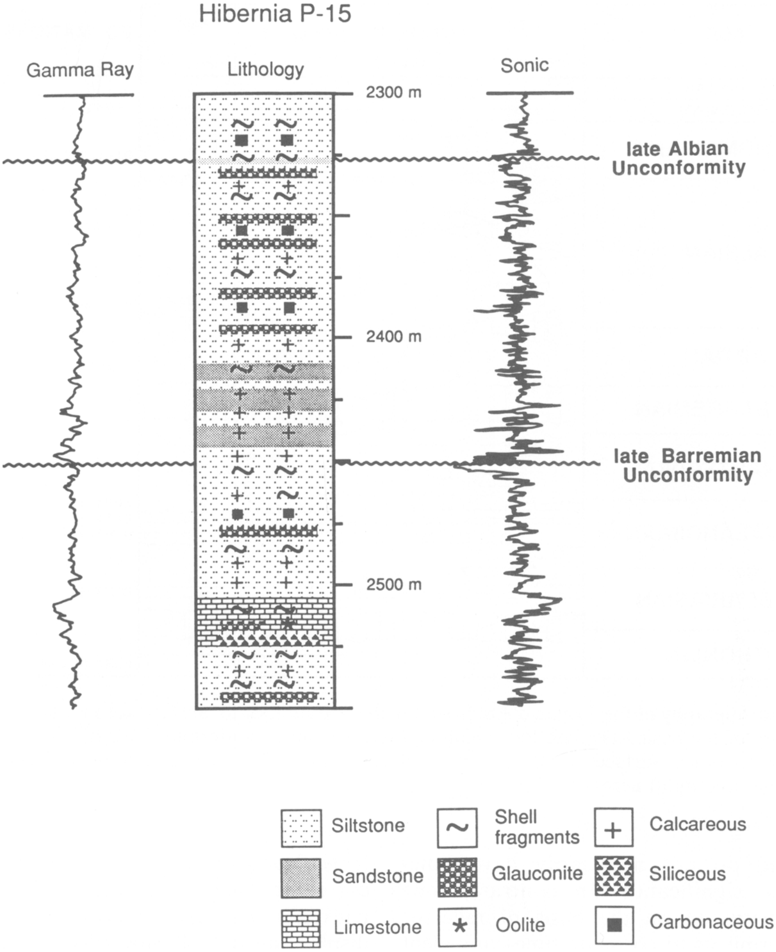


Fig. 16. Exploratory well Hibernia P-15 is located on the southern flank of the Nautilus transfer zone. See Fig. 2 for exact location. Correlation of the unconformities determined on the basis of stratal relationships observed in the seismic reflection data to lithology and geophysical logs is shown. Note that the late Barremian unconformity correlates with the base of a blocky marine sandstone.

from glauconitic, calcareous shale to shelly sandstone (Figs 10 and 16). Palynomorphs from both Hibernia P-15 and B-27 indicate that the oldest rocks overlying the unconformity are of late Albian age. Furthermore, at Hibernia O-35 well (*c.* 2184–2200 m beneath KB), close to the Nautilus transfer zone, upper Albian very fine-grained, highly carbonaceous sandstones were recovered above the unconformity and are quite different to the lower Albian sandstones beneath the unconformity.

Lithostratigraphy and subsidence history

The late Barremian to late Aptian and the late Aptian to late Albian sequences correspond roughly to the Avalon and Ben Nevis formations in the Jeanne d'Arc basin (Fig. 17; Grant *et al.* 1988; McAlpine 1991). According to the subdivisions suggested by McAlpine (1991), the Avalon Formation can be subdivided into three units: (1) a basal unit characterized by vari-coloured shale, (2) a middle unit composed predominantly of sandstone, and (3) an upper unit that is a coarsening-upward sandstone-dominated unit. The Ben Nevis Formation is defined by McAlpine (1991) as the first fining-upward succession overlying the Avalon Formation. Basinward both of these formations pass laterally into the Nautilus Shale (Fig. 6; McAlpine 1991). Formations are defined on the basis of lithic characteristics and stratigraphic

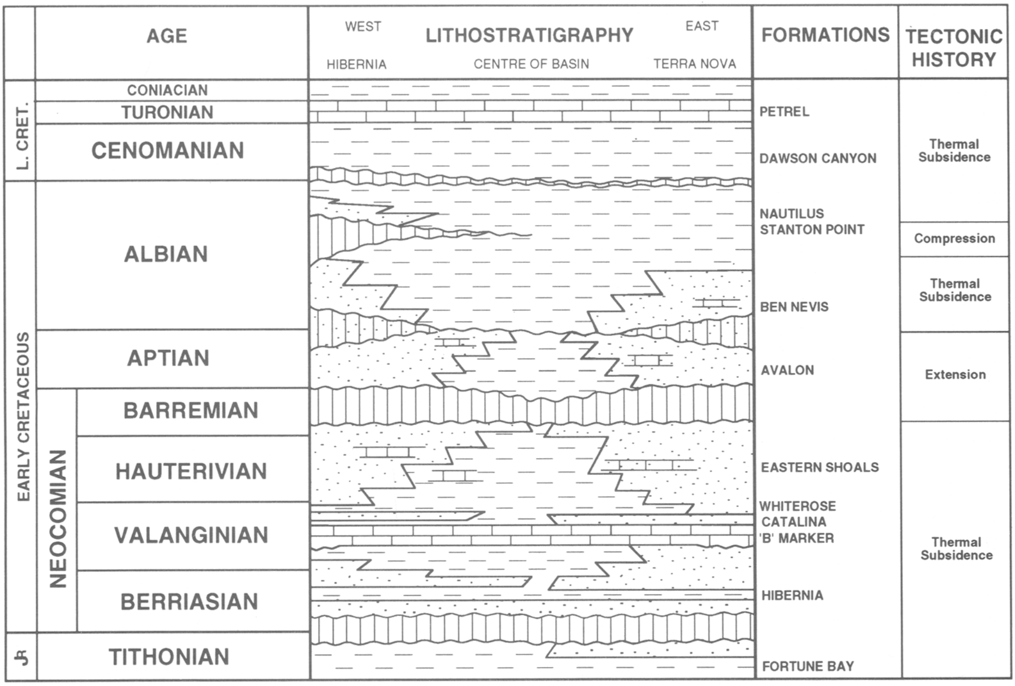


Fig. 17. Lithostratigraphy of the Jeanne d'Arc basin for the late Jurassic to late Cretaceous and its relation to the tectonic history of the basin. The late Barremian and late Aptian unconformities are rift onset unconformities that correlate to onlap surfaces in the seismic reflection data. The late Albian unconformity documents compression-induced uplift across the basin.

position and do not necessarily have time-stratigraphic significance. In contrast, time surfaces determined on the basis of reflector geometry permit us to correlate time-equivalent coarse-grained proximal facies to the fine-grained distal facies within the basin (Fig. 17).

Our detailed seismic sequence analysis of the Jeanne d'Arc basin for the late Jurassic to late Cretaceous allows us to link the lithostratigraphy with the tectonic history of the basin (Fig. 17). The late Barremian and late Aptian unconformities are interpreted as rift onset unconformities, recording the formation of a physiographic hole, and they are characterized in seismic reflection data by well-developed onlap. An alternative interpretation, that the unconformities are primarily due to eustatic fluctuations during a time of more-or-less continuous block tilting, is not consistent with the absence of predicted lowstand deposits in the closed palaeobathymetric lows. The increase in accommodation associated with these extensional events is significantly greater than the sediment input to the basin as evidenced by the fact that the seismic reflectors overlying these unconformities all onlap onto a single surface (Figs 7 and 8). The Avalon Formation, which correlates to one of these onlapping seismic packages, is a variable siliciclastic sequence and displays an overall upward-shoaling trend, that in places, is accompanied by an upward-coarsening trend in response to sediments infilling the physiographic hole (Fig. 17). Consequently, the extensional events are followed by periods of tectonic quiescence as recorded by these onlapping packages that shoal upward as the available space fills with sediment. Conversely, if the sedimentation kept pace with the differential subsidence, then a fanning pattern of seismic reflectors would develop with each successive layer of sediment onlapping the previous horizon at or near the same position. This is not observed. In addition, minimal variations in palaeowater-depth and facies distribution would occur if the sedimentation kept pace with the subsidence rate.

The erosional truncation associated with the late Albian unconformity is best developed along the intersection between transfer zones (Nautilus and Ammonite) and border faults (Murre and Mercury; Figs 4 and 10). This truncation registers the reactivation and inversion of the same crustal blocks that were involved in the extension process. During the late Albian, palaeowater depths along the transfer zones increased toward the east away from the border faults, and thus the deformed sediments overlying the transfer zones in the eastern portion of the Jeanne d'Arc basin were not truncated. Consequently, the upper Albian sandstones, derived from the cannibalization of the underlying sequences, have a very limited aerial distribution in the basin (Fig. 17).

The large magnitude of the post-Aptian thermal subsidence, a function of mantle extension, is not consistent with the minor late Barremian to late Aptian brittle crustal extension (Figs 6–8). In addition, because of the elapsed time since the late Triassic and inferred middle/late Jurassic extensional deformation (*c.* 60–200 Ma), it is difficult to explain the observed post-Aptian thermal subsidence by this earlier phase of extension in the Jeanne d'Arc basin. Therefore, we propose that the large magnitude of post-Aptian thermal subsidence associated with the rather minor late Barremian–late Aptian brittle deformation observed in the basin results from the Grand Banks region moving off the Newfoundland hotspot and the re-equilibration of the lithosphere to normal thicknesses beginning in the late Aptian (e.g., Newfoundland Seamounts, Fig. 1). The Grand Banks region was associated with volcanism, which we attribute to the Newfoundland hotspot, prior to the late Jurassic/early Cretaceous (Jansa & Pe-Piper, 1988). Because lithospheric cooling rates are directly proportional to the lithospheric thickness, the close proximity of the hotspot modifies the equilibrium of the cooling extending lithosphere. Consequently, while the Grand Banks remained in close spatial proximity to the Newfoundland hotspot, its rate of subsidence was less than that for normal cooling lithosphere. While this mechanism accounts for diminished rates of lithospheric subsidence, it does not explain the accelerated rates and the large magnitude of subsidence subsequent to the late Barremian–late Aptian rifting. However, we note that seafloor spreading moved the Grand Banks away from the proximity of the hotspot after breakup, thus allowing extended lithosphere to re-equilibrate thermally to normal lithospheric thickness (*c.* 120 km) with a concurrent increase in subsidence rates. Jansa & Pe-Piper (1988) dated basalts dredged from the Newfoundland Seamounts as 97 ± 1.7 Ma indicating that the Grand Banks region had moved off the hotspot by at least late Albian time, timing that is consistent with the increased thermal subsidence in the Jeanne d'Arc basin.

Conversely, if significant lower crustal and mantle extension occurred across the Grand Banks with only minor upper crustal deformation during the late Barremian to late Aptian time, then this style of extensional deformation could also account for the observed subsidence patterns across the Grand Banks. Such a distribution of extension implies the existence of a westward dipping intracrustal detachment that effectively thins the lower crust and generates thermal-type subsidence across the region. We require that this detachment has a ramp-flat-ramp geometry such that it breached the surface close to the position of the continent–ocean boundary (Fig. 1; eastern edge of the Newfoundland basin). The 'flat' component of the detachment occurred at mid-crustal depths across the Grand Banks region and ramped again beneath the North American continent. In this interpretation, the Grand Banks represents an upper plate margin and is separated from the lower plate margin (i.e., Iberia) by a westward dipping detachment (e.g., Enachescu 1987; Tankard & Welsink 1987; Keen & deVoogd 1988).

Isopach map

Multi-channel stacking velocities and velocity information derived from well data were used to convert two-way travel time into sedimentary thickness in order to create the late Barremian–late Aptian isopach map. The isopach map illustrates the regional distribution and the overall northward-thickening of the upper Barremian to upper Aptian sediments in the Jeanne d'Arc basin (Fig. 18). Within portions of the highly faulted Nautilus transfer zone, only the late Barremian and late Albian bounding unconformities could be confidently identified. Identification of the late Aptian unconformity on the basis of stratal patterns in the highly faulted region proved to be difficult (Fig. 18).

Thick accumulations of upper Barremian–upper Aptian sediments are preferentially preserved along the border faults (e.g., Mercury K-76 and Hibernia G-55; Fig. 18). The thickness and distribution of the syn-rift sediments, together with the marine magnetic anomalies, are consistent with our inferred WNW extension direction (Figs 2 and 18). Toward the south, a thick wedge of sediment was deposited near the intersection of the Egret border fault and the Egret transfer zone (Fig. 18). An erosional channel approximately 15 km wide can be traced away from the depocentre across the Murre subbasin (Fig. 18). The late Barremian depocentre near the intersection of the Egret border fault

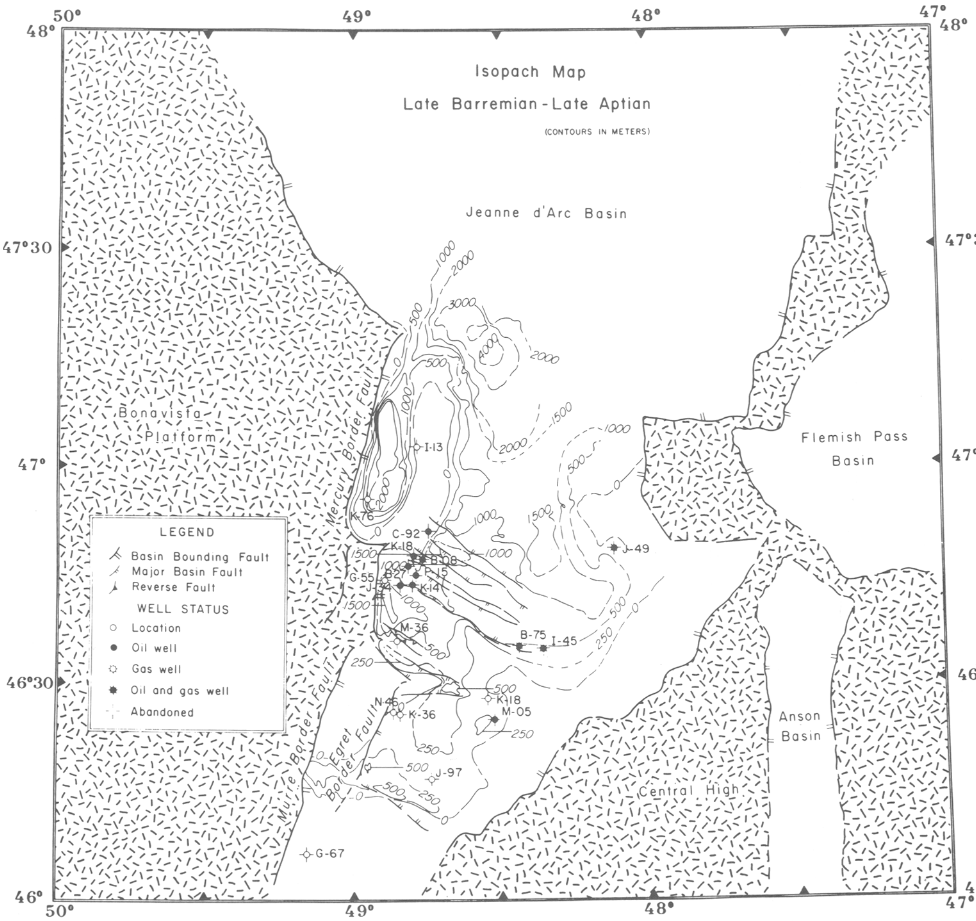


Fig. 18. Isopach map illustrating the regional distribution of upper Barremian to upper Aptian sediments. Note the influence of the border fault transfer zone geometry on the thickness of the sediments. The overall sediment thickness increases across the transfer zones toward the north within the basin.

and the Egret transfer zone, and the distribution and configuration of the 250 m contour toward the north within the basin suggest that the erosional channel was a major conduit for sediment to enter the southern Jeanne d'Arc basin at this time.

A pronounced increase in sediment thickness is observed along the central segment of the Murre border fault just north of the Ammonite transfer zone (Fig. 18). The upper Barremian–upper Aptian sediment thickness in this region exceeds 1500 m. Exploratory well Hibernia G-55 is located on the northern edge of this depocentre and sampled thick accumulations of coarse-grained clastic rocks (Fig. 6; *c.* 1000 m). The subdued rift flank topography near the intersection of the Murre border fault and the Ammonite transfer zone might have allowed fluvial drainage systems access to the basin (Fig. 18).

Thick accumulations of upper Barremian to upper Albian sediments (*c.* 2000 m, Mercury K-76) are preserved in the Mercury sub-basin, which is located north of the Nautilus transfer and west of the Flying Foam structure. Seismic reflection profiles across and along the Bonavista platform indicate that there is little if any evidence for erosional down-cutting that might be associated with large drainage systems traversing the platform and supplying sediment to the Mercury sub-basin. This could be the consequence of the highly indurated meta-sedimentary rocks composing the Bonavista platform or the very low gradients across the platform precluding large amounts of erosional downcutting, or both.

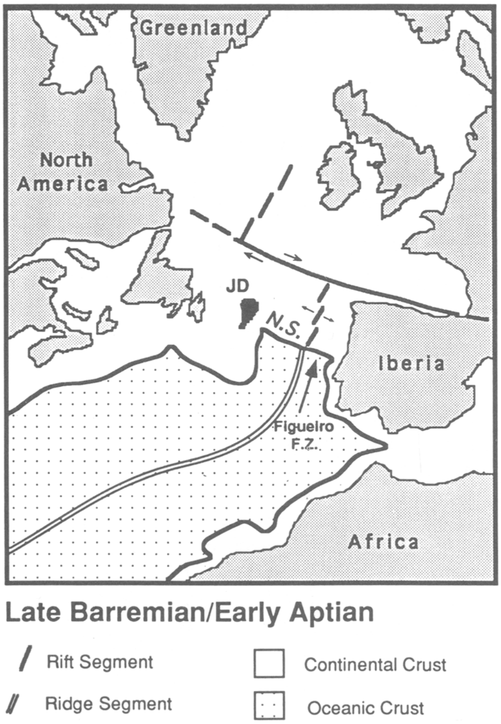


Fig. 19. A generalized reconstruction of the North Atlantic during the late Barremian/early Aptian showing the boundary between continental and oceanic crust. The Newfoundland Seamounts (N.S.)/ Figueiro fracture zone separates regions undergoing continued continental extension toward the north from regions in the south where seafloor spreading had already begun. Gravity and magnetic lineations across the Grand Banks indicate that the eastern continuation of the Egret transfer zone in the Jeanne d'Arc basin (JD) is roughly coincident with the Newfoundland Seamounts offshore.

Late Barremian to late Aptian extension

Seismic reflection data indicate that the late Barremian–late Aptian and the late Aptian–late Albian sequences are faulted and offset. Within the transfer zones, the sequences are highly faulted and deformed. The fault displacement and relief of the intrabasinal highs associated with the transfer zones diminishes basinward. The deformation within the transfer zones appears to record the three-dimensional collapse of the hanging-wall blocks near the termination of border fault segments (Fig. 4). Growth faults and expanded sedimentary sections developed across faults on the down-thrown blocks are observed only within the late Barremian–late Aptian sequence. From our analysis, large fault-controlled accommodation generated during both late Barremian and late Aptian time is evidenced by the seismic reflection profiles, exploratory well data, and isopach map (Figs 6–18). Therefore, on the basis of these observations and the previously mentioned criteria necessary to identify a break-up unconformity, we conclude that the late Barremian and late Aptian unconformities observed in the Jeanne d'Arc basin are not 'break-up unconformities' as previously interpreted or modelled (Enachescu 1987; Tankard & Welsink 1987; Meador *et al.* 1988; Cloetingh *et al.* 1989; Kusznir & Egan 1989; Tankard *et al.* 1989; Tucholke *et al.* 1989). In fact, to the contrary, these unconformities are rift-onset unconformities documenting renewed phases of rifting. In our interpretation, rifting in the Jeanne d'Arc basin continued to at least late Aptian time with the overlying sediment representing the thermal phase of subsidence associated with this last phase of rifting on the Grand Banks.

The thickness of upper Barremian to upper Aptian sediments in the Jeanne d'Arc basin systematically increases across the transfer zones from south to north within the discrete sub-basins (Fig. 18). In conjunction with an increase in sediment thickness, there is also an increase in the number of upper Barremian to upper Albian rotated and divergent sedimentary packages observed within the northern sub-basins. Consequently, the structural depth to the late Barremian unconformity increases from south to north within the sub-basins (Tankard & Welsink 1987; Tankard *et al.* 1989). Correlation of the seismic reflection and well data indicates that the overall northward dip of the basin predominantly developed after the late Barremian (e.g., Tankard *et al.* 1989). Decompaction and backstripping of sediments from exploratory wells in the Jeanne d'Arc basin demonstrate a marked increase in the basement subsidence during the late Barremian (*c.* 120 Ma; Hiscott *et al.* 1990).

Implications for break-up

As previously mentioned, new interpretations of the magnetic data north of the Newfoundland Seamounts suggest that seafloor spreading between the northern portion of the Newfoundland basin and the northern Iberian margin began after the early Aptian, timing indistinguishable from the timing of rift cessation in the Jeanne d'Arc basin determined by sequence

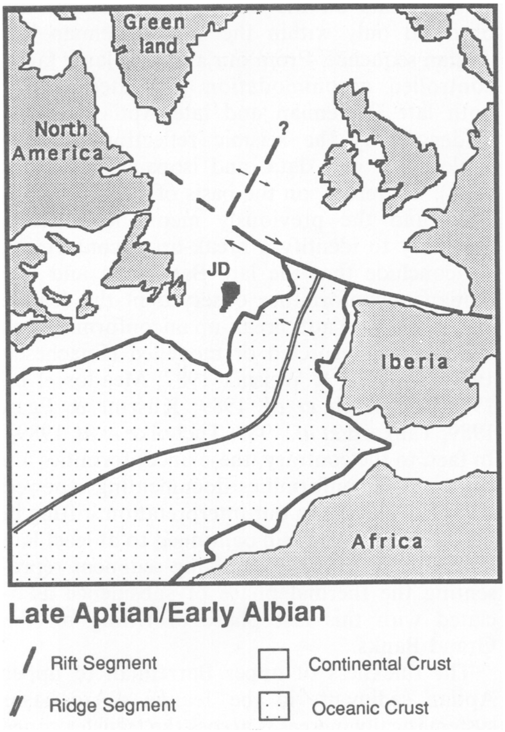


Fig. 20. A generalized reconstruction of the North Atlantic during the late Aptian/early Albian showing the boundary between regions undergoing continental extension and regions undergoing seafloor spreading. Note that the northward propagation of seafloor spreading is predicted to occur abruptly, jumping from one transfer zone to the next as extension exceeds some threshold.

analysis. Gravity and magnetic lineations across the Grand Banks indicate that the eastern continuation of the Egret transfer zone is roughly coincident with the trend of the Newfoundland Seamounts offshore (Welsink *et al.* 1989). The Egret transfer zone is an important structural boundary separating the southern and central Jeanne d'Arc basin (Fig. 4). Upper Barremian to upper Albian sediments are not preserved in the southern Jeanne d'Arc basin (Fig. 18). In fact, in the southern Jeanne d'Arc basin the late Barremian unconformity separates dipping and truncated upper Jurassic/lower Cretaceous sediments from the overlying upper Cretaceous sediments (e.g., Murre G-67). Consequently, we propose that the onset of seafloor spreading in the southern Newfoundland basin began by at least late Barremian to early Aptian time consistent with the predictions of Tucholke *et al.* (1989; Fig. 19). However, this is not the case for the northern Newfoundland basin.

The Newfoundland Seamounts and Figueiro fracture zone delineated a spatial and temporal boundary that separated seafloor spreading in the south from continental extension to the north. On the basis of the observed deformational structures and distribution of syn-rift sediment, together with the trend of the oldest marine magnetic anomalies (Fig. 2), we propose that the extension direction was predominantly west-northwest to west. The onset of seafloor spreading in the northern Newfoundland basin was concomitant with the late Aptian cessation of rifting in the Jeanne d'Arc basin (Fig. 20). Because the northward propagation of seafloor spreading in the region (Figs 19 and 20) took place during the Cretaceous quiet zone (*c.* 120–84 Ma), it is difficult to determine from the magnetic lineations whether the northward propagation of seafloor spreading occurred continuously (i.e., 'zipper' opening) or by a series of abrupt events where the onset of seafloor spreading jumped across transfer zones from one segment to the next. Nevertheless, the abrupt change in the late Barremian to late Aptian extensional deformation across the Egret transfer zone in the Jeanne d'Arc basin (Fig. 18) suggests that the northward propagation of seafloor spreading in this region occurred by a catastrophic jump from the southern Newfoundland basin to the northern Newfoundland basin in late Aptian times. We propose that the nature of how seafloor spreading propagates, be it gradual or catastrophic, is related to the proximity of the region to the pole of opening and to large offset transfer zones that can effectively displace the deformation away from the extending region. The propagation of seafloor spreading between the Kerguelen–Heard Plateau and Broken Ridge has also been interpreted to have occurred by a catastrophic jump across a transfer zone (Driscoll *et al.* 1989).

An alternative interpretation of the marine magnetic data, suggesting that seafloor spreading between the central Grand Banks and Iberia began at or before magnetic anomaly M0 time, requires that rifting and block rotation in the Jeanne d'Arc basin were contemporaneous with seafloor spreading. This interpretation would challenge the existing paradigm that the brittle deformation of extended continental lithosphere ceases when seafloor spreading begins (Falvey 1974; Cathles & Hallam 1991; Karner *et al.* 1993). It is difficult to understand in two-dimensions how tensional forces would be maintained within the plate, given the existence of the nascent ridge crest and the attendant compressional forces associated with ridge push. The northward propagation of seafloor spreading and the counter-clockwise rotation of the extension direction in the North Atlantic, however, could have generated a complex three-dimension stress field thereby reactivating the brittle deformation in regions already undergoing seafloor spreading. If this interpretation is correct, then we infer that a transfer zone separated regions that were undergoing rifting in the north (i.e., between Flemish Cap and Goban Spur) from regions where seafloor spreading had already commenced (i.e., between central Grand Banks and Iberia). In this scenario, rifting between Flemish Cap and Goban Spur influenced regions south of the transfer zone, thus reactivating crustal blocks in the Jeanne d'Arc basin even though seafloor spreading was occurring toward the east between the central Grand Banks and Iberia.

Conclusions

In summary, the tectonic and stratigraphic evolution of the Jeanne d'Arc basin resulted from a number of rifting events beginning in the late Triassic and culminating in the late Aptian. The previously interpreted early Aptian breakup unconformity is actually a rift-onset unconformity documenting a late Barremian phase of extension. The rotation and divergence of the seismic reflectors above this unconformity attest to differential subsidence due to localized block rotation during rifting. In the rift basin, the late Barremian unconformity marks the transition from subaerial to submarine deposition. That is, the onlap patterns observed in the seismic reflection data, which define the unconformity, are actually recording a marine flooding surface within the basin. This increase in accommodation is further evidence of continued extension within the Jeanne d'Arc basin at this time. The unconformity related to the last phase of rifting is dated as late Aptian. In our interpretation, the unconformity related to the last phase of rifting is also recording the onset of seafloor spreading. The overlying sediments would then represent the thermal subsidence following this last phase of rifting.

Recent studies indicate that magnetic anomaly M0 is not well resolved north of the Newfoundland Seamounts within the Newfoundland basin (Cande *et al.* 1988; Enachescu, 1988; Srivastava *et al.* 1990) and is not present north of the Figueiro fracture zone along the conjugate Iberian margin (Whitmarsh *et al.* 1990). This new interpretation of the magnetic data north of the Newfoundland Seamounts suggests that seafloor spreading between the northern portion of the Newfoundland basin and the northern Iberian margin began after the early Aptian, timing that is indistinguishable from the cessation of rifting in the Jeanne d'Arc basin determined by sequence analysis. Consequently, we propose that the onset of seafloor spreading in the northern Newfoundland basin was concomitant with the late Aptian cessation of rifting in the Jeanne d'Arc basin.

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References

AUSTIN, J. A., Jr., TUCHOLKE, B. E. & UCHUPI, E. 1989. Upper Triassic–Lower Jurassic salt basin southeast of the Grand Banks. *Earth and Planetary Science Letters*, **92**, 357–370.

BOILLOT, G. & WINTERER, E. L. 1988. Drilling on the Galicia margin: retrospect and prospect. *In:* BOILLOT, G., WINTERER, E. L., MEYER, A. W. ET AL. (eds) *Proceedings of the Ocean Drilling Program, Scientific Results*, **103**, College Station, TX, 809–828.

CANDE, S. C. ET AL. 1989. *Magnetic lineations of the world's ocean basins*. AAPG Map series.

CATHLES, L. M. & HALLAM, A. 1991. Stress-induced changes in plate density, Vail sequences, epeirogeny, and short-lived global sea level fluctuations. *Tectonics*, **10**, 659–671.

CHANG, H. K., KOWSMANN, R. O. & DE FIGUEIREDO, A. M. F. 1988. New concepts on the development of the east Brazilian marginal basins. *Episodes*, **11**, 194–202.

CHRISTIE-BLICK, N. & DRISCOLL, N. W. 1995. Sequence Stratigraphy. *Annual Review of Earth and Planetary Sciences*, **23**, 451–478.

CLOETINGH, S., TANKARD, A. J., WELSINK, H. J. & JENKINS, W. A. M. 1989. Tectonic linkage and Mesozoic of Eastern Canada, an explanation for Vail's coastal onlap curves: *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*. AAPG Memoir, **46**, 283–293.

DRISCOLL, N. W. 1992. *Tectonic and Depositional Processes Inferred from Stratal Relationships*. PhD thesis, New York, Columbia University.

——— & HOGG, J. R. 1995. Stratigraphic Response to Basin Formation: Jeanne d'Arc Basin, Offshore

Newfoundland. *In:* LAMBIASE, J. J. (ed.) *Hydrocarbon Habitat in Rift Basins*. Geological Society, London, Special Publication **80**, 145–163.

———, KARNER, G. D. & CHRISTIE-BLICK, N. 1990. Stratigraphic Evidence from Jeanne d'Arc basin for the Timing of Break-up Between Grand Banks and Iberia. (Abst.) *EOS*, **71**, 1563.

———, ——— & WEISSEL, J. K. 1989*a*. Unconformities: Are Variations of In-Plane Force a Viable Mechanism for Their Formation? (Abst.) *EOS*, **70**, 1345.

———, ——— & ——— 1989*b*. Stratigraphic and tectonic evolution of Broken Ridge from seismic stratigraphy and Leg 121 drilling. *In:* PEIRCE, J., WEISSEL, J. K. ET AL. *Proceedings of the Ocean Drilling Program, Initial Reports*, **121A**, 71–93, College Station, TX.

EBINGER, C. J. & TUCHOLKE, B. E. 1988. Marine geology of Sohm Basin, Canadian Atlantic Margin. *American Association of Petroleum Geologists Bulletin*, **72**, 1450–1468.

EMBRY, A. F. & DIXON, J. 1990. The break-up unconformity of the Amerasia basin, Arctic Ocean: evidence from Arctic Canada. *Geological Society of America Bulletin*, **102**, 1526–1534.

ENACHESCU, M. E. 1987. Tectonic and structural framework of the northeast Newfoundland continental margin. *In:* BEAUMONT, C. & TANKARD, A. J. (eds) *Sedimentary Basins and Basin-forming Mechanisms*, CSPG Memoir, **12**, 117–146.

——— 1988. Extended basement beneath the intracratonic rifted basins of the Grand Banks of Newfoundland. *Canadian Journal of Exploration Geophysics*, **24**, 48–65.

FALVEY, D. A. 1974. The development of continental margins in plate tectonic theory. *APEA Journal*, **14**, 95–106.

FROSTICK, L. E. & REID, I. 1989. Is structure the main control of river drainage and sedimentation in rifts? *Journal of African Earth Sciences*, **8**, 165–182.

GRANT, A. C., JANSA, L. F., MCALPINE, K. D. & EDWARDS, A. 1988. Mesozoic–Cenozoic geology of the eastern margin of the Grand Banks and its relation to Galicia Bank. *In:* BOILLOT, G. WINTERER, E. L. ET AL. *Proceedings of the Ocean Drilling Program, Scientific Results*, **103**, 787–808.

HAWORTH, R. T. & KEEN, C. E. 1979. The Canadian Atlantic Margin, a passive continental margin encompassing an active past. *Tectonophysics*, **59**, 83–126.

HEGARTY, K. A., WEISSEL, J. K. & MUTTER, J. C. 1988. Subsidence history of Australia's southern margin: constraints on basin models: *American Association of Petroleum Geologists Bulletin*, **72**, 615–633.

HISCOTT, R. N., WILSON, R. C. L., GRADSTEIN, F. M., PUJALTE, V., GARCIA-MONDEJAR, J., BOUDREAU, R. R. & WISHART, H. A. 1990. Comparative stratigraphy and subsidence history of Mesozoic rift basins of North Atlantic. *American Association of Petroleum Geologists Bulletin*, **74**, 60–76.

HUBBARD, R. J. 1988. Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins. *American Association of Petroleum Geologists Bulletin*, **72**, 49–72.

———, PAPE, J. & ROBERTS, D. G. 1985. Depositional sequence mapping to illustrate the evolution of a passive continental margin. *In:* BERG, O. R. & WOOLVERTON, D. (eds) *Seismic Stratigraphy II: an integrated approach to hydrocarbon exploration*. AAPG Memoir, **39**, 93–115.

JANSA, L. F. & PE-PIPER, G. 1988. Middle Jurassic to early Cretaceous igneous rocks along eastern North American Continental Margin. *American Association of Petroleum Geologists Bulletin*, **72**, 347–366.

——— & WADE, J. A. 1975. Geology of the Continental margin off Nova Scotia and Newfoundland. *In: Offshore Geology of Eastern Canada*. Geological Survey of Canada Paper, **74-30**, 51–105.

KARNER, G. D., DRISCOLL, N. W. & WEISSEL, J. K. 1993. Response of the lithosphere to in-plane force variations. *Earth and Planetary Science Letters*, **114**, 397–416.

KEEN, C. E. & BARRETT, D. L. 1981. Thinned and subsided continental crust on the rifted margin of eastern Canada: crustal structure, thermal evolution and subsidence history. *Geophysical Journal of the Royal Astronomical Society*, **65**, 443–465.

——— & DE VOOGD, B. 1988. The continent–ocean boundary at the rifted margin off eastern Canada: new results from deep seismic reflection studies. *Tectonics*, **7**, 107–124.

———, BOUTILIER, R., DE VOOGD, B., MUDFORD, B. & ENACHESCU, M. E. 1987. Crustal geometry and extensional models for the Grand Banks, Eastern Canada: constraints from deep seismic reflection data. *In:* BEAUMONT, C. & TANKARD, A. J. (eds) *Sedimentary Basins and Basin-forming Mechanisms*. Canadian Society of Petroleum Geologists Memoirs, **12**, 101–115.

KENT, D. V. & GRADSTEIN, F. M. 1985, A Cretaceous and Jurassic geochronology. *Geological Society of America Bulletin*, **96**, 1419–1427.

KLITGORD, K. D. & SCHOUTEN, H. 1986. Plate kinematics of the central Atlantic. *In:* VOGT, P. R. & TUCHOLKE, B. E. (eds) *The western north Atlantic Region*. The Geology of North America, **17**, Geological Society of America, 351–378.

———, HUTCHINSON, D. R. & SCHOUTEN, H. 1988. U.S. Atlantic continental margin, structural and tectonic framework. *In: The geology of North America, The Atlantic Continental Margin*, Geological Society of America, **I-2**, 19–55.

KUSZNIR, N. J. & EGAN, S. S. 1989. Simple-shear and pure-shear models of extensional sedimentary basin formation: application to the Jeanne d'Arc basin, Grand Banks of Newfoundland. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, AAPG Memoir, **46**, 305–322.

LAMBIASE, J. J. 1991. A model for tectonic control of lacustrine stratigraphic sequences in continental rift basins. *In:* KATZ, B. J. (ed.) *Lacustrine basin exploration*, AAPG Memoir, **50**, 265–276.

LEEDER, M. & GAWTHORPE, R. 1987. Sedimentary models for extensional tilt-block/half-graben basins, *In:* COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (eds) *Continental Extensional Tectonics*, Geological Society, London, Special Publication, **28**, 139–152.

MAUFFRET, A. & MONTADERT, L. 1987. Rift tectonics on the passive continental margin off Galicia (Spain). *Marine and Petroleum Geology*, **4**, 49–70.

———, MOUGENOT, D., MILES, P. R. & MALOD, J. A. 1989. Results from multichannel reflection profiling of the Tagus Abyssal Plain (Portugal)—Comparison with the Canadian Margin. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*. AAPG Memoir, **46**, 379–394.

MCALPINE, K. D. 1991. *Mesozoic stratigraphy, sedimentary evolution, and petroleum potential of the Jeanne d'Arc basin, Grand Banks of Newfoundland.* Geological Survey of Canada Paper 1–50.

MCCLAY, K. R. & SCOTT, A. D. 1991. Experimental models of hangingwall deformation in ramp-flat listric extensional fault systems. *Tectonophysics*, **188**, 85–96.

MCHONE, J. G. 1988. Tectonic and paleostress patterns of Mesozoic intrusions in eastern North America. *In:* MANSPEIZER, W. (ed.) *Triassic–Jurassic Rifting: Continental Breakup and the origin of the Atlantic Ocean and passive margins.* Developments in Geotectonics, **22**, 607–620.

MCPHERSON, J. G., SHANMUGAM, G. & MOIOLA, R. J. 1987. Fan-deltas and braid-deltas: varieties of coarse-grained deltas. *Geological Society of America Bulletin*, **99**, 331–340.

MEADOR, K. J. & AUSTIN, J. A. 1988. Seismic comparison of the early stratigraphic evolution of conjugate passive continental margins: the Newfoundland/Flemish basin and the eastern Iberian Abyssal plain south of Galicia Bank. *In:* BOILLOT, G., WINTERE, E. L. ET AL., *Proceedings of the ODP, Scientific. Results*, **103**, College Station, TX (Ocean Drilling Program), 777–786.

———, ——— & DEAN, D. F. 1988. Shelf to basin correlations in the Newfoundland Basin. *In:* BALLY, A. W. (ed.) *Atlas of Seismic Stratigraphy.* AAPG Studies in Geology, **27**, **2**, 88–95.

MITCHUM, R. M. Jr. 1977. Seismic stratigraphy and global changes of sea level, Part 11 Glossary of terms used in seismic stratigraphy. *In:* CLAYTON, C. E. (ed.) *Seismic Stratigraphy—Application to Hydrocarbon Exploration.* AAPG Memoir **26**, 205–212.

MONTADERT, L., DE CHARPAL, O., ROBERTS, D., GUENNOC, P. & SIBUET, J.-C. 1979. Northeast Atlantic passive continental margins: rifting and subsidence processes. *In:* TALWANI, M., HAY, W. & RYAN, W. B. F. (eds) *Deep drilling results in the Atlantic Ocean; continental margins and paleoenvironment.* AGU, Maurice Ewing Series, **3**, 154–186.

MORLEY, C. K., NELSON, R. A. PATTON, T. L. & MUNN, S. G. 1990. Transfer zones in the East African rift system and their relevance to hydrocarbon exploration in rifts. *American Association of Petroleum Geologists Bulletin*, **74**, 1234–1253.

PEMBERTON, S. G., BROMLEY, G. G. & EKDALE, A. A. 1984. *Ichnology the use of trace fossils in sedimentology and stratigraphy.* SEPM Shortcourse notes.

POSAMENTIER, H. W., JERVEY, M. T. & VAIL, P. R. 1988. Eustatic controls on clastic deposition I. *In:* WILGUS, C. K., HASTINGS, B. S., KENDALL, C. G., POSAMENTIER, H. W., ROSS, C. A. & VAN WAGONER, J. C. (eds) *Sea level changes: An integrated approach.* SEPM Special Publication, **42**, 109–124.

ROYDEN, L. & KEEN, C. E. 1980. Rifting processes and thermal evolution of the continental margin of eastern Canada determined from subsidence curves. *Earth and Planetary Science Letters*, **51**, 343–361.

SRIVASTAVA, S. P., SCHOUTEN, H., ROEST, W. R., KLITGORD, K. D., KOVACS, L. C., VERHOEF, J. & MACNAB, R. 1990. Iberian plate kinematics: a jumping plate boundary between Eurasia and Africa. *Nature*, **344**, 756–759.

———, ROEST, W. R., KOVACS, L. C., OAKEY, G., LEVESQUE, S., VERHOEF, J. & MACNAB, R. 1990. Motion of Iberia since the late Jurassic: results from detailed aeromagnetic measurements in the Newfoundland basin. *Tectonophysics*, **184**, 229–260.

——— & TAPSCOTT, C. R. 1986. Plate kinematics of the North Atlantic. *In:* VOGT, P. R. & TUCHOLKE, B. E. (eds) *The geology of North America, Volume M: The western North Atlantic*, Geological Society of America, 379–404.

TANKARD, A. J. & WELSINK, H. J. 1987. Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland. *AAPG Bulletin*, **71**, 1210–1232.

———, ——— & JENKINS, W. A. M. 1989. Structural styles and stratigraphy of the Jeanne d'Arc basin, Grand Banks of Newfoundland. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins.* AAPG Memoir, **46**, 265–282.

TODD, B. J., REID, I & KEEN, C. E. 1988. Crustal structure across the southwest Newfoundland Transform Margin. *Canadian Journal of Earth Sciences*, **25**, 744–759.

TUCHOLKE, B. E., AUSTIN, J. A. Jr. & UCHUPI, E. 1989. Crustal structure and rift-drift evolution of the Newfoundland Basin: *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, AAPG Memoir, **46**, 247–264.

UNDERHILL, J. R. 1991. Controls on late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: a critical test of a key section of Exxon's original global cycle chart. *Basin Research*, **3**, 79–98.

VAIL, P. R. 1987. Seismic stratigraphy interpretation utilizing sequence stratigraphy. *In:* BALLY, A. W. (ed.) *Atlas of Seismic Stratigraphy*, AAPG Studies in Geology, **27**, **1**, 1–10.

———, MITCHUM, R. M. Jr., TODD, R. G., WIDMIER, J. M., THOMPSON, S. III, SANGREE, J. B., BUBB,

J. N. & HATELID, W. G. 1977, Seismic stratigraphy and global changes of sea level. *In:* CLAYTON, C. E. (ed.) *Seismic Stratigraphy—Application to Hydrocarbon Exploration*, AAPG Memoir, **26**, 49–212.

VAN WAGONER, J. C., POSAMENTIER, H. W., MITCHUM, R. M. Jr., VAIL, P. R., SARG, J. F. LOUTIT, T. S. & HARDENBOL, J. 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. *In:* WILGUS, C. K., HASTINGS, B. S., KENDALL, C. G., POSAMENTIER, H. W., ROSS, C. A. & VAN WAGONER, J. C. (eds) *Sea Level changes: An integrated approach*. SEPM Special Publication, **42**, 39–45.

VERHOEF, J. & SRIVASTAVA, S. P. 1989. Correlation of sedimentary basins across the North Atlantic as obtained from gravity and magnetic data, and its relation to the early evolution of the North Atlantic. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, AAPG Memoir, **46**, 131–148.

WELSINK, H. J. & TANKARD, A. J. 1988. Structural and stratigraphic framework of the Jeanne d'Arc basin, Grandbanks. In: BALLY, A. W. (ed.) *Atlas* of Seismic Stratigraphy. AAPG Studies in Geology, **27**, **2**, 14–22. ———, SRIVASTAVA, S. P. & TANKARD, A. J. 1989. Basin architecture of the Newfoundland Margin and its relationship to ocean crust fabric during extension. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*. AAPG Memoir, **46**, 197–214.

WHITE, N. J., JACKSON, J. A. & MCKENZIE, D. P. 1986. The relationship between the geometry of normal faults and that of the sedimentary layers in their hanging walls. *Journal Structural Geology*, **8**, 897–909.

WHITMARSH, R. B., MILES, P. R. & MAUFFRET, A. 1990. The ocean–continent boundary off the western continental margin of Iberia — I. Crustal structure at 40° 30′N. *Geophysical Journal International*, **103**, 509–531.

ZIEGLER, P. A. 1989. Evolution of the North Atlantic—An overview. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, AAPG Memoir **46**, 111–130.