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Chapter 18

Vail's Coastal Onlap Curves and Their Correlation with Tectonic Events, Offshore Eastern Canada

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ABSTRACT

Vail's coastal onlap curves conventionally have been attributed to glacio-eustatic sea-level variations, but they show a better correlation with tectonic events. The tectonic and structural evolution of the Canadian Atlantic continental margin is recorded in the history of extensional subsidence of the Mesozoic basins underlying the Grand Banks and the Scotian Shelf. Large-scale unconformity-bounded sequences match the major basin-forming stages representing rift and postrift subsidence. Smaller scale local unconformities and regional limestone markers reflect adjustments to intermittent subsidence. This tectono-stratigraphic record, the timing and patterns of sea-floor spreading, and Vail's coastal onlap curves correspond closely, suggesting broad-scale tectonic linkage. Intermittent phases of accumulated tensional stresses that are associated with the rift episodes and subsequent rapid relaxation of these stresses may explain asymmetry in the relative onlap charts. Both the timing and nature of Vail's second-order and third-order cycles appear to be controlled by plate-tectonic evolution and the associated changes in the intraplate stress regimes of the central North Atlantic. The correspondence between Vail's cycles and the tectono-stratigraphic anomalies on the Grand Banks and offshore Nova Scotia suggests intraplate stress as the common cause.

INTRODUCTION

Mesozoic and Cenozoic coastal onlap curves constructed by Vail et al. (1977) and Haq et al. (1987) in an attempt to produce a global stratigraphic frame of reference are biased toward the North Atlantic margins. Their cycles are not so much global, therefore, as a seismic stratigraphic record for the extensional and passive-margin basins bordering the North Atlantic Ocean (Miall, 1986; Hallam, 1988). Parkinson and Summerhayes (1985) and Miall (1986) questioned the global nature of the coastal onlap curves, as we do here, and suggested that synchroneity of relative sea-level changes is regional rather than global. The question of global synchroneity is important because it is the basis for arguments favoring glacio-eustatic rather than tectonic origin for short-term changes.

Intraplate stresses play a crucial role in basin formation, where lithospheric stretching requires tensional stress levels of several kilobars (Cloetingh and Nieuwland, 1984; Houseman and England, 1986). The effects of these stresses on the subsequent evolution of sedimentary basins, however, have largely been ignored in geodynamic modeling. Recent work by Cloetingh et al. (1985) and Cloetingh (1986) has demonstrated that temporal fluctuations in intraplate stress levels provide a tectonic explanation for the short-term sea-level variations inferred from the stratigraphic record. In contrast, Vail and coworkers have attributed short-term cyclic variations in onlap/offlap patterns to glacio-eustatic processes. This preference was based primarily on the "apparent" synchronous global nature of sea-level variations, as well as the lack of a tectonic mechanism to explain the third-order cycles. Previous authors (e.g., Bally, 1982; Watts, 1982) have argued for a tectonic explanation but were unable to identify a tectonic mechanism operating on a time scale that would explain the observed short-term changes in sea level. Because little geological or geochemical evidence exists for significant Mesozoic and Cenozoic glacial events prior to the mid-Tertiary (Pitman and Golovchenko, 1983), plate dynamics and associated changes in stress levels in the plate interiors would appear to provide a more probable explanation for basin stratigraphy.

The directions of present-day stress fields, derived from analysis of well breakouts (Bell and Gough, 1979; Bell, in press) and analysis of earthquake focal mechanisms (Bergman and Solomon, 1985), are consistent in plate interiors. Microstructures record ancient stress fields in the lithosphere (Letouzey, 1986; Bergerat, 1987; Philip, 1987) and show that temporal variations in the observed long-wavelength spatially coherent stress patterns do occur. These observations provide strong evidence for large-scale rotation of the ancient stress fields and also suggest that the state of stress can vary on a relatively short time scale (Philip, 1987) comparable to Vail's third-order cycles (2-5 m.y.). Numerical modeling has demonstrated a causal relationship between the processes at plate boundaries and the deformation in plate interiors (Richardson et al., 1979; Wortel and Cloetingh, 1981, 1983; Cloetingh and Wortel, 1985, 1986; Johnson and Bally, 1986). Progress has also been made in unravelling the linkage between plate kinematics and plate dynamics. Significant deviations can occur between directions of stress predicted by plate motion vectors and the stress trajectories actually observed in plates bounded by subduction zones (Zoback, in press). Comparison of ancient stress fields and present-day stress directions in non-convergent plates shows close agreement between predictions based on changes in plate motion vectors and observed stress trajectories. Examples include the North American plate, in which the stress field is oriented as predicted by ridge push models (Zoback et al., 1986), and the northwestern European Platform (Klein and Barr, 1986; Letouzey, 1986). A feature shared by all plates is the regional consistency of the overall fan-shaped stress patterns that are undisturbed by lateral intraplate heterogeneities (Bergman and Solomon, 1985; Cloetingh and Wortel, 1985, 1986).

These observations may explain the timing and patterns of rift and postrift subsidence off eastern Canada. Previous chapters in this volume address the tectono-stratigraphic evolution of the Nova Scotian and Newfoundland margins, namely: (1) The extensional basins have evolved by reactivation of pre-Mesozoic fabrics. (2) The trends of major transfer faults, including the Newfoundland and Charlie Gibbs transform margins, are collinear with ocean-floor fracture zones, implying tectonic linkage between continental and oceanic crust. (3) Unconformity-bounded sequences within the Mesozoic-Cenozoic sedimentary basins are attributed to intermittent fault-controlled subsidence. (4) These sequence boundaries correlate fairly precisely with Vail's stratigraphy as well as with the principal magnetic anomalies in the oceanic crust, suggesting a possible tectonic interpretation (Tankard and Welsink, 1987). Hubbard (1988) has argued that most megasequence and sequence boundaries of the Grand Banks, Arctic Beaufort, and Brazilian Santos basins have tectonic overprints. Similarly, Hallam (1988) has attempted to relate Jurassic unconformities beneath the North Sea and their correlatives on Vail's charts to fault-controlled subsidence.

This chapter elaborates on these studies. It explores the possibility that tectonic linkage of oceanic and continental lithosphere and transmission of stress over large distances have caused short-period phases of vertical motion in the rifted lithosphere. The Mesozoic part of Vail's stratigraphy is intimately related to the extensional history of the North Atlantic, whereas the Cenozoic part of the curve may preserve some evidence of a compressional intraplate stress regime, glacio-eustatic sea-level fluctuations notwithstanding.

SEQUENCE STRATIGRAPHY

The timing and characteristics of rift basin formation and postrift subsidence off eastern Canada reflect a stepwise opening of the central North Atlantic. Prominent episodes in this kinematic history occurred in the Middle Jurassic, Early Cretaceous, and Late Cretaceous when eastern Canada was separated from Africa, Iberia, and Europe respectively (Tankard and Welsink, 1987, 1989). In this study we consider the Jeanne d'Arc and Scotian basins. These basins have been the focus of much recent exploration activity and their stratigraphies are well known. The post-rift era started in the Bajocian in the Scotian basin, but much later, in the Aptian, in the Jeanne d'Arc basin so that separate different extensional events can be distinguished and contemporaneous rift and postrift stratigraphies can be compared. The two basins formed in different basement terranes and incorporate significantly different structural styles.

Figure 1 summarizes the stratigraphy of the Scotian and Jeanne d'Arc basins. It compares the sequence boundaries in these basins with Vail's global stratigraphic framework (Haq et al., 1987) and with the ages of ocean-floor magnetic anomalies (Klitgord and Schouten, 1986). To reconcile the stratigraphic-geomagnetic database, we have adopted the DNAG geologic time scale (Palmer, 1983). Biostratigraphic analysis of Grand Banks wells, in particular, is based on standards established for the North Sea. Magnetic anomalies pertaining to the central North Atlantic are keyed to the geomagnetic time scale of Kent and Gradstein (1985) and are plotted against the DNAG time scale (Palmer, 1983; Klitgord and Schouten, 1986; Srivastava et al., 1988). Klitgord and Schouten discuss the assumptions behind interpretation of the magnetic anomalies. Anomalies ECMA, M0, and 34 provide important benchmarks that record sequential opening of the Atlantic Ocean, and correlate with prominent postrift or breakup unconformities. The data shown in Figure 1 appear to be internally consistent.

Use of the DNAG time scale required that the Vail coastal onlap curves be redisplayed while continuing to honor the biochronozones used. The redisplayed charts have been

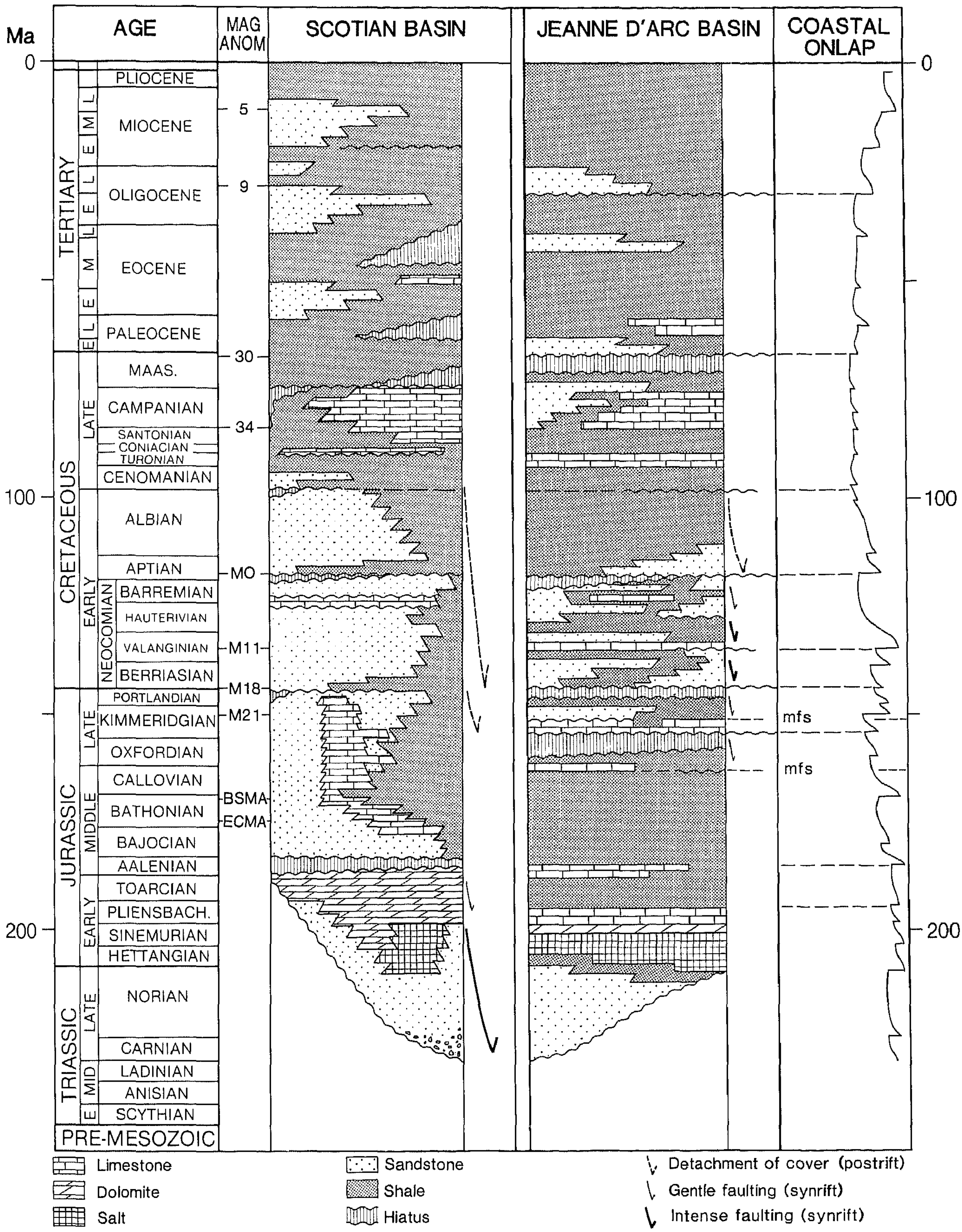


Figure 1—Stratigraphic columns for the Jeanne d'Arc and Scotian basins off eastern Canada, showing major basin-forming stages based on seismic stratigraphy and biostratigraphic analysis (after Welsink, Dwyer and Knight, 1989; Tankard et al., 1989). Curve of coastal onlap/offlap after Haq et al. (1987), adjusted to DNAG time scale (Palmer, 1983). Magnetic anomalies after Klitgord and Schouten (1986) and Srivastava et al. (1988). (mfs = maximum flooding surface)

simplified somewhat because of space limitations. Figure 1 shows a close correlation between Jeanne d'Arc basin, Scotian basin, and Vail sequence boundaries. Correlation is particularly close for the Oxfordian-Aptian interval in the Jeanne d'Arc basin which is based on palynology. Less well control is available below the Oxfordian, and less detailed investigation has been conducted above the Aptian. The absence of a correlative sequence boundary in Figure 1, consequently, may reflect only a lack of information.

Jeanne d'Arc Basin

Exploration activity has focused on the Upper Jurassic and Lower Cretaceous synrift succession, which contains several unconformity-bounded sequences. Structures developed during this episode of rifting were superimposed on earlier structural trends and would have obliterated any direct evidence of fault-controlled subsidence that might have existed in the pre-Late Jurassic basin. Table 1 summarizes the characteristics of each sequence boundary for the Jeanne d'Arc basin.

Early and Middle Jurassic

Vail's sequence boundaries can be correlated with evaporites and several transgressive carbonate sequences, including the Aalenian Whale limestone (Jansa et al., 1976). The sequence boundaries encapsulate the transgressive intervals. Hubbard (1988) recognizes a sequence boundary within the Bathonian.

In the upper Callovian an interval of potential source rocks is referred to the *lamberti-athleta* Zones of the standard ammonite zonal scheme (Table 1) on the basis of work done by one of us (W.A.M.J.) for Esso Resources Canada Ltd. Along the southeastern margin of the basin this interval is associated with a minor unconformity and stratigraphic onlap (Tankard et al., 1989). We attribute this source bed to the maximum flooding surface of Haq et al. (1987, their figure 4). Biostratigraphic control suggests that the Callovian sedimentary record is not interrupted by substantial unconformities.

Late Jurassic

Lower Oxfordian sediments of *mariae-cordatum* age occur consistently, but middle Oxfordian *tenuiserratum-glosense* age deposits are more locally distributed. Lower Kimmeridgian sediments commonly rest unconformably upon the lower Oxfordian, and more locally upon the middle Oxfordian (Table 1). The Kimmeridgian is represented by a sequence in which transgressive Egret limestones onlap the Oxfordian-Kimmeridgian unconformity. The principal oil source rock of the Jeanne d'Arc basin lies within the Egret Formation and is associated with a maximum flooding stage during *autissiodorensis-elegans* time. This source rock occurs basinwide, but shows partition of the basin by transfer faults (Tankard et al., 1989). The climax of fault-controlled subsidence is reflected in the coarse-grained Jeanne d'Arc progradational facies.

Early Cretaceous

The Late Jurassic pattern of fault-controlled subsidence and fluvial influx was repeated in the Berriasian at the onset of the Cretaceous. In the Hibernia oil field the reservoir intervals show marked rollover and thickening into the listric basin-forming fault. Accumulation was influenced by relay structures (Tankard et al., 1989, their figures 17 and 18). Many of these faults appear to terminate at the Valanginian sequence boundary. A fundamental change in basin morphology occurred in the mid-Valanginian when the basin widened beyond the rift shoulders, eliminating terrestrial depositional systems and resulting in more open marine circulation. This change in the pattern of subsidence was abrupt and is recognized within or close to the B marker (Tankard et al., 1989). Haq et al. (1987) identified the subsequent boundary as a third-order event.

Hauterivian-Barremian deposition was broadly transgressive but was interrupted by several smaller scale (1-2 m.y.) fluctuations. Even at this scale, the Avalon succession in the Hibernia field was punctuated by transgressive shales that match the third-order cycles of Haq et al. (1987). However, structural control of deposition was pronounced; it governed rollover into major listric faults, reservoir geometries and maturity by relay structures, and major displacements along transfer faults. The basal Aptian breakup unconformity (Table 1) terminates the synrift succession. It marks fundamental changes in palynofacies and marine biota, and in the patterns of subsidence, sedimentation, and marine circulation.

Table 1. Characteristics of sequence boundaries in the Jeanne d'Arc basin.

Maastrichtian/Paleocene	Uppermost Cretaceous generally missing.
Albian/Cenomanian	Seismic unconformity, no obvious palynofacies or biostratigraphic changes.
Early Aptian	Hiatus represents late Barremian time. Diverse marine dinoflagellate assemblages below; impoverished marginal marine assemblages above.
Mid-Valanginian B marker	Changes in paleogeography and marine circulation. Higher energy, restricted marine and nonmarine deposition below; lower energy, normal salinity, open marine deposition above.
Jurassic/Cretaceous	Marked by unconformity that commonly represents late Portlandian time and part of early Portlandian (post-*albani*) time. Upper Berriasian is generally present.
Principal source rock	Kimmeridgian *autissiodorensis-elegans* Zones, equivalent to maximum flooding stage.
Oxfordian/Kimmeridgian	Unconformity representing lower Kimmeridgian (all or some of *baylei-eudoxus* Zones), upper Oxfordian, and locally middle Oxfordian (*tenuiserratum* Zone).
Callovian	Callovian sedimentary record essentially complete. Source rock referred to *lamberti-athleta* Zones, corresponding to maximum flooding stage.

Aptian-Albian sedimentation took place in a broad epeiric sea and has the classic characteristics of deposition in such a setting. Northward deepening of the basin and detachment of the cover sequence are attributed to the farfield effects of Orphan basin extension. Whereas the direction of Late Jurassic-Early Cretaceous extension was toward the southeast, post-Neocomian tensional stress fields were oriented approximately SW-NE . The principal stress orientations derived from well breakout populations (Bell, in press) corroborate this interpretation.

A basal Cenomanian hiatus is recognized in the seismic-reflection data, but apart from shallowing of the epeiric sea, this event is not marked by major palynofacies or biostratigraphic changes.

Scotian Basin

The Scotian basin is a composite of several smaller rift basins. Late Triassic-Early Jurassic rifting was followed by a long period of passive-margin development. Unconformity-bounded sequences recording intermittent phases of rift and postrift subsidence (Figure 1) are interpreted from seismic stratigraphy (Given, 1977; Welsink, Dwyer, and Knight, 1989). These sequences differ in depositional characteristics and syndepositional deformation.

An Aalenian unconformity terminates the rifting episode. Although it is a major unconformity in the Scotian basin, its only correlative in the Jeanne d'Arc basin is the Whale limestone. Generally, the sequence boundaries in the Scotian basin are less well defined than in the Jeanne d'Arc basin. This is because of the conformable nature of the Scotian basin succession in the distal parts of the postrift terrace wedge. Recognition of subtle onlap and offlap relationships is also inhibited by seismic resolution. The Scotian basin sequence boundaries are less constrained biostratigraphically than those in the Jeanne d'Arc basin.

Summary

Large-scale unconformity-bounded sequences match stages of basin formation that represent rift and postrift subsidence. Internally, the various sequence boundaries correlate with the second-order and third-order boundaries of Haq et al. (1987). Synsedimentary faulting in the Jeanne d'Arc basin controls dispersal patterns, lithology, and geometries of the stratigraphic units. Many faults appear to terminate at sequence boundaries (e.g., B marker).

Events such as the basal Kimmeridgian unconformity, B marker, and Aptian breakup unconformity mark fundamental changes in the styles of subsidence and sedimentation. In the case of the B marker, biostratigraphic evidence suggests a change more rapid than can be explained by thermal subsidence alone.

Major sequence boundaries in the Jeanne d'Arc and Scotian basins appear to be correlative but differences between them are evident. For example, the Aptian unconformity in the Jeanne d'Arc basin is a major sequence boundary characterized by truncation and onlap relationships, whereas its correlative in the Scotian basin is a minor unconformity beneath a transgressive shale. The Aptian unconformity in the Jeanne d'Arc basin is directly related to the separation of Iberia, but in the Scotian basin these extensional stress fields were more remote.

Rifting resulted in the formation of oceanic crust between Nova Scotia and Africa much earlier than between the Grand Banks and Iberia (Figure 1), yet the sequence stratigraphies as predicted by Haq et al. (1987) are consistently similar. Tectonic linkage between continental and oceanic crust (Welsink, Srivastava and Tankard, 1989) and the structural control of sedimentation reflect tectonic processes.

STRESS-INDUCED VERTICAL MOTIONS AND BASIN STRATIGRAPHY

North Atlantic intraplate stress levels and orientations have changed with kinematic history and plate behavior. Examples include changes in plate motion and spreading rates, ridge jumps, and propagating spreading centers. Reorientation of the tensional stress directions from NW-SE during the Late Jurassic and Early Cretaceous to SW-NE in the Late Cretaceous have been inferred from regional transfer fault azimuths and well breakout information (Tankard et al., 1989, Bell, in press). These trends correspond to adjacent ocean-floor flow lines and fracture zones (Welsink, Srivastava, and Tankard, 1989; Srivastava et al., 1988). Similar relationships have also been demonstrated from the Neogene of the Dead Sea (Livnat et al., 1987). These changes in intraplate stress modify the patterns of basin subsidence that are generally attributed to mechanisms such as thermal contraction of the lithosphere and sediment loading.

Figure 2 shows the stress-induced uplift at the flank of the basin and three types of synthetic stratigraphy. In the absence of intraplate stress, progressive widening of the basin results from cooling (Figure 2A) (Watts, 1982). Figures 2B and 2C show the same conditions but with a transition to 500-bar tension or relaxation of tension superimposed. Thermally induced flexural widening is an adequate explanation for prolonged phases of coastal onlap in a rifted basin. However, these long-term characteristics fail to reproduce the punctuated nature of the stratigraphy. Figures 2B and 2C show that inclusion of intraplate stresses in elastic models of rift-basin evolution can account for the succession of alternating onlaps and offlaps commonly observed along the flanks of basins. Figure 2 also shows that the stress-induced subsidence/uplift perturbations change sign and magnitude according to intrabasinal position, thus enabling one to discriminate between the tectonic and eustatic components of relative sea level. Out-of-phase intrabasinal cycles such as those described by Embry (in press) can also be explained by this model.

Tensional stresses decline during rifting and subsequent breakup. Rifting that formed the margins of the North Atlantic occurred in several phases and involved stepwise relaxation of tensional stresses as the ocean basin opened sequentially. This process might explain the enigmatic high-amplitude sea-level fluctuations of the Cretaceous that do not correlate either with spreading-rate discontinuities or with ridge propagation (Schlanger, 1986). Similarly, the correlation of short-term sea-level fluctuations across the Atlantic may reflect rift-related accumulation and relaxation of tensional stresses. Thus, the accumulation of tensional stresses induces periods of apparent rise of sea level. These are followed by shorter periods of relative lowering of sea-level associated with rapid relaxation of tensional stresses. Toward the end of the rift episode relative sea level should rise, and then subside during breakup. Breakup unconformities are commonly observed in the stratigraphic record of passive margins and are attributed to lowering of sea level as the ocean opens (Haq et al., 1987). In the Jeanne d'Arc basin the basal Aptian unconformity marks separation of the Grand Banks from Iberia (anomaly M0). Intermittent phases of accumulated tensional stresses and subsequent rapid relaxation of these stresses explain the asymmetry in

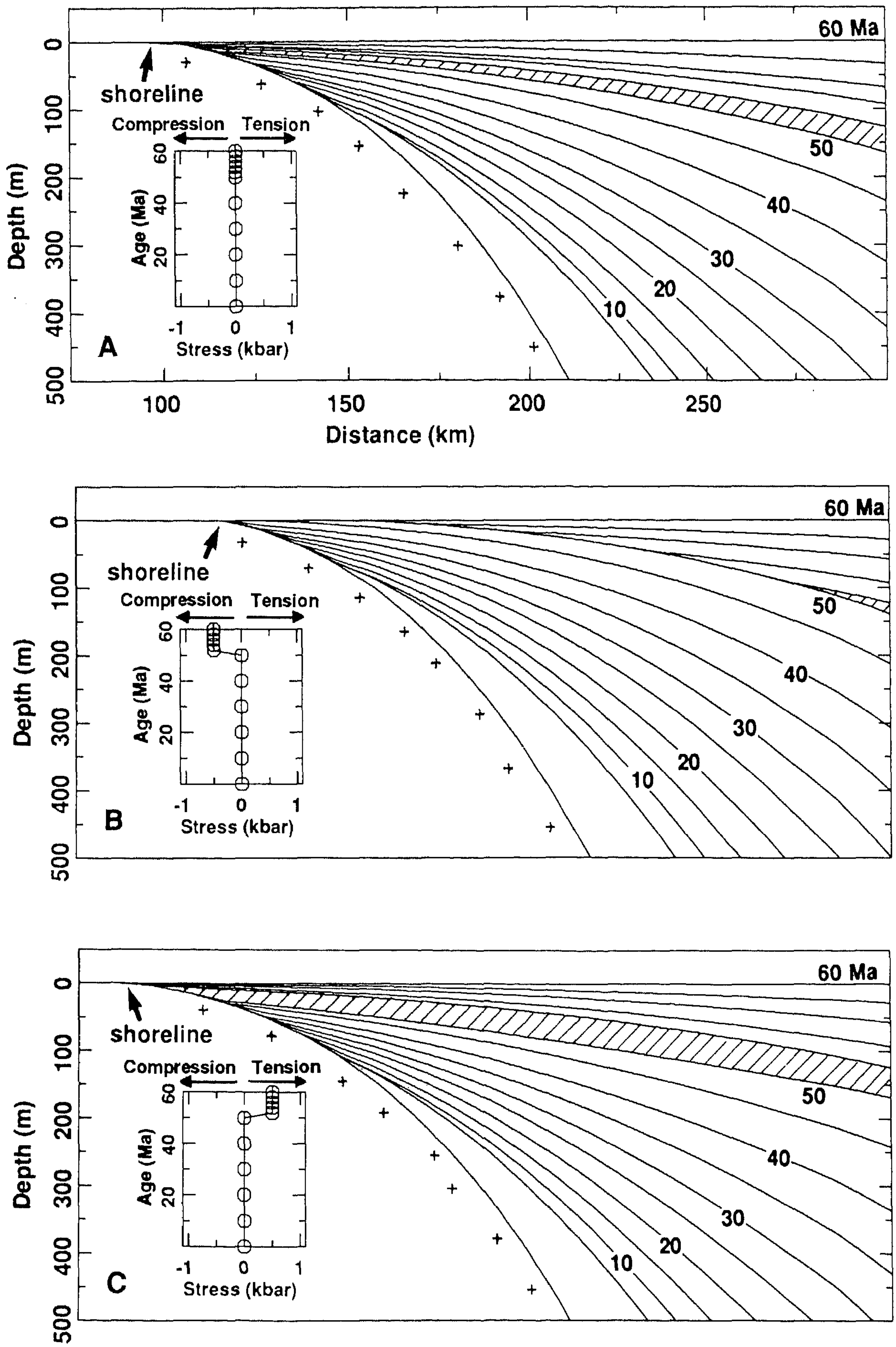

60 Ma
shoreline
Compression
Tension
Age (Ma)
Stress (kbar)
Depth (m)
Distance (km)
A
B
C
10
20
30
40
50
0
100
200
300
400
500
150
250
-1
1
60

Figure 2—Stratigraphic expression of stress-induced uplift/subsidence at basin margin. (A) Long-term widening of rifted basin in the absence of intraplate stress. (B) Short-term phase of relaxation of tensional stress (equivalent to an increase in compressional stress level) induces rapid uplift at the basin flank and produces a short-term phase of basin offlap. (C) Effect of an increased level of tension on basin stratigraphy, causing a short-term phase of basin onlap. (After Cloetingh et al., 1985.)

the Haq et al. onlap/offlap charts. These breakup unconformities have not been explained successfully by geodynamic models that exclude the effects of intraplate stresses. Differences in the rheological structure of the lithosphere that influence its response to applied intraplate stresses may result in different magnitudes of sea-level change.

ANCIENT STRESS FIELDS OF THE CENTRAL NORTH ATLANTIC

Cloetingh et al. (in press) described the effects of intraplate stresses on stratigraphic models of the Atlantic margin of the United States. The stratigraphy of this margin has been documented extensively (e.g., Poag, 1985) and has been the subject of detailed quantitative modeling (e.g., Steckler et al., 1988). Cloetingh et al. used a modeling approach similar to that of Steckler et al. (1988), including a two-layered stretching model for basin initiation. However, they also incorporated the effects of multiple and finite phases of stretching and intraplate stresses in the stratigraphic model. Evidence for Early Cretaceous extension and northward propagation of the Atlantic rift system (Tankard and Welsink, 1987; Ziegler, 1988) and the results of analysis of subsidence of the Atlantic margin of the United States (Greenlee et al., 1988) support the occurrence of multiple phases of stretching.

Standard elastic models of basin evolution do not adequately predict the commonly observed geometry of sedimentary basins (Figure 3A). This geometry has been attributed either to the response of the basin to visco-elastic relaxation (Sleep and Snell, 1976) or to long-term eustatic lowering of sea-level (Watts and Thorne, 1984). We attribute much of the observed character of the sedimentary wedge, including erosion and depositional thinning, to stress-induced uplift of the edge of the basin. Similarly, short-term changes in intraplate stress levels can produce the lower Eocene and Oligocene onlap/offlap relationships. Figure 3B shows the best fit to the stratigraphy to a two-layered stretching model and an elastic rheology, incorporating long-term sea-level changes after Kominz (1984) and a fluctuating intraplate stress level. The stratigraphy of the United States Atlantic margin can be simulated by relaxation of the Mesozoic tensional intraplate stress fields and a transition to compressional stress that increases during the Tertiary.

The stress field inferred from stratigraphic modeling of the U.S. Atlantic margin is shown in Figure 4. The upper limits of stress levels are derived from elastic models for basin stratigraphy. Incorporation of depth-dependent brittle-ductile rheology lowers these predicted stress levels. The long-term trend of the paleostress pattern suggests a change from overall rift-related tension during the Mesozoic to a stress regime characterized by compression in the Tertiary. Superimposed on this long-term trend are several abrupt changes. Both the character and timing of these changes are largely consistent with independent data on the kinematic evolution of the central and North Atlantic (Klitgord and Schouten, 1986). From 175 to 59 Ma rifting in the Atlantic evolved from initiation of the Gulf of Mexico-Central Atlantic-Ligurian Tethys spreading (175 Ma) by a number of discrete steps (170, 150, 132, 119, 80, 67 Ma; Figure 1), to separation of the European-Greenland plate from North America 59 m.y. ago. The stress curve inferred from the stratigraphy of the U.S. Atlantic margin suggests that rifting events that occurred about 180 m.y. ago were associated with pronounced relaxation of tensional stresses followed by renewed accumulation of tension.

Comparison of the Tertiary part of the stress curve with the tectonic history of the North Atlantic relaxation of tensional stresses and transition to a more neutral stress regime about 50 m.y. ago coincided with termination of Thulean volcanism and opening of the Greenland-Rockall-Norwegian Sea (Ziegler, 1988, 1989). Similarly, transition to a more compressional stress regime coincided with the Caribbean and the Pyrenean orogenies and cessation of spreading in the Labrador Sea (Klitgord and Schouten, 1986). Sea-floor spreading ended in the Labrador Sea at the same time as widespread uplift, shelf shallowing, and coastal erosion occurred (Balkwill, 1987); these features are consistent with an increase in the level of compressional stress. The change in the compressional stress level at the time of the mid-Oligocene regression coincided with a major plate reorganization in the central Atlantic.

The inferred transition in the horizontal stress field is broadly supported by plate kinematic history. The transition from overall tension in the Mesozoic to a more compressional regime during the Cenozoic also agrees with Hubbard's (1988) study of sequence boundaries in the Beaufort, Grand Banks, and Santos basins. Whereas Mesozoic sequence boundaries are attributed to rifting, Cenozoic unconformities in the Arctic correspond to a period of compression. In this context, the stress curve derived from the sea-level record of the North Sea also shows a change from a long-term tensional stress regime during Jurassic-Cretaceous times to a more compressional stress regime during the Tertiary (Lambeck et al., 1987). These observations are supported by stratigraphic modeling that incorporates intraplate stress (Kooi and Cloetingh, 1989). The calculated stress curve mimics the transition from rift-wrench related tectonics during the Mesozoic to compressional tectonics during the Tertiary in northwestern Europe (Ziegler and van Hoorn, 1989).

Stress fields obviously can be propagated over long distances (Letouzey, 1986; Ziegler, 1988) to the extent that they resemble "global changes." For example, a major change in the northeast Atlantic or even the Gulf of Mexico and Caribbean can affect the northwest Atlantic. Significant changes in plate trajectories might have influenced the global stress field (Pollitz, 1988), especially where the magnitude of these stresses approaches lithospheric failure. The rigid nature of lithospheric plates ensures that prominent tectonic phases are interregional and broadly synchronous. Tectonism and the stratigraphic response commonly show small differences from one basin to the next (Hubbard, 1988; Tankard and Balkwill, 1989).

The broad-scale features of the stress curves derived from U.S. Atlantic margin stratigraphy and North Sea stratigraphy correspond to the tectono-stratigraphic patterns recognized in the offshore basins of eastern Canada (Figure 1).

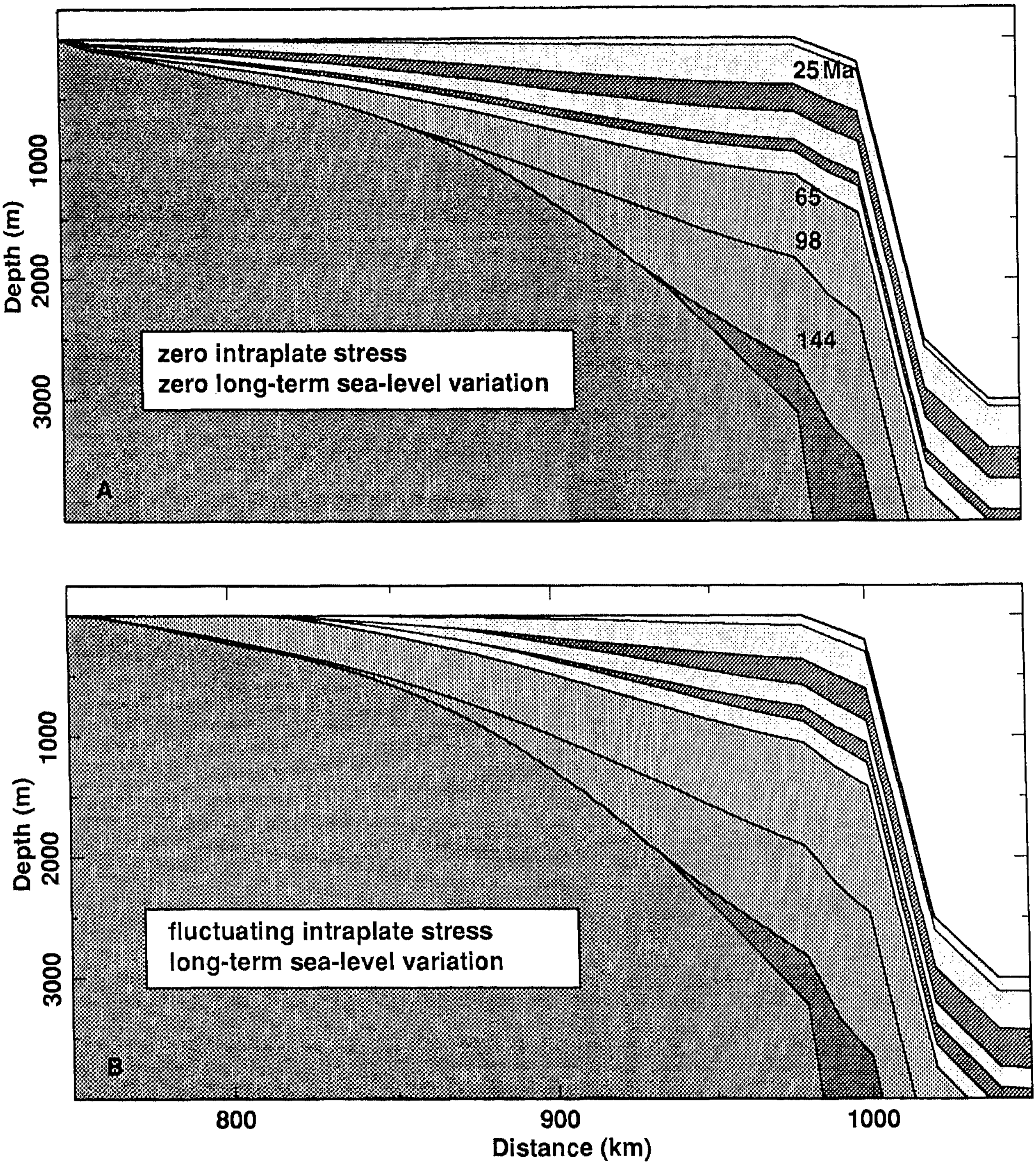
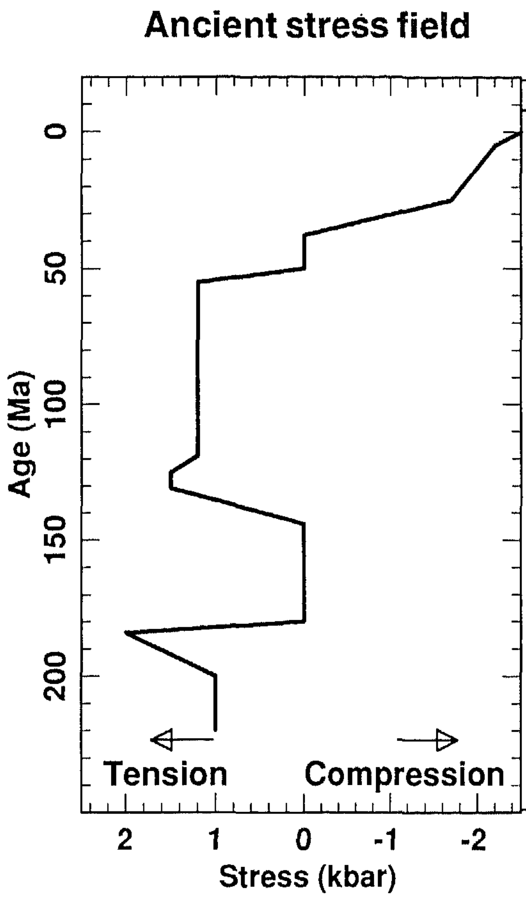


Figure 3—Modeled Atlantic margin stratigraphy of the United States. (A) Best fit to stratigraphy for two-layered stretching model in absence of intraplate stress. (B) Best fit to basin stratigraphy incorporating long-term sea-level changes after Kominz (1984) and a fluctuating intraplate stress level in stratigraphic modeling (after Cloetingh et al., 1988).

Stratigraphic modeling of the effects of intraplate stresses on the basins off eastern Canada is in progress. Nevertheless, the present comparison does demonstrate that the stratigraphic record of the Grand Banks and Scotian basins not only records the kinematic evolution of the central North Atlantic (Figure 1) but also reflects the dynamics of the forces that drive the plates. While changes in plate motion and geometric adjustment to spreading occur, stress levels may be



Atlantic plate motion

Anomaly	Age (Ma)	Atlantic tectonic events
2	2.5	reorganization spreading Atlantic sfs
5c	17	Jan Mayen ridge jump
9	28	African plate boundary jump
13	36	Labrador sea-floor spreading abandoned
21	50	major changes in C. Atlantic spreading
24/25	58	break-up Greenland-Rockall
34	80	Labrador sea-floor spreading starts
M0	119	North Atlantic rifting (Biscay-Rockall-Norwegian Sea) separation Grand Banks-Iberia
M21	150	separation of Africa-Nova Scotia
ECMA	175	Gulf of Mexico-Central Atlantic sea-floor spreading starts East Coast Magnetic Anomaly

Figure 4—Ancient stress field from stratigraphic modeling of U.S. Atlantic margin (after Cloetingh et al., in press). Timing of plate-tectonic events in the central and North Atlantic after Klitgord and Schouten (1986). Vertical arrows indicate transition from overall rift-related tensional stress regime to one characterized by compression during the Tertiary.

amplified to levels exceeding those typically associated with spreading processes (about 500 bar), to levels capable of rupturing the lithosphere (several kbars).

CONCLUSIONS

The overall synchroneity in the timing of sea-level changes and associated unconformities for margins on opposite sides of the Atlantic Ocean reflects a similar tectonic history, which is in turn closely linked to the kinematic and dynamic evolution of the Atlantic-Tethyan system. Both the timing and nature of Vail's second-order and third-order cycles appear to be controlled by plate-tectonic processes and associated changes in the intraplate stress regimes in the central and North Atlantic. The correspondence between Vail's cycles and the tectono-stratigraphic anomalies in the Jeanne d'Arc and Scotian basins suggests intraplate stress as a common cause. The timing and nature of these cycles to a large extent reflect the tectonic evolution of the central North Atlantic. In this study we have specifically addressed the tectonic justification for relative coastal onlap, although we admit that the relative sea-level curve may have been overprinted locally by secondary eustatic processes; for example, the glacio-eustatic fluctuations of the Cenozoic. In the Hettangian of the Jeanne d'Arc basin there is also a systematic repetition of evaporite-shale units not recognized by Haq et al. (1987).

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REFERENCES CITED

Balkwill, H.R., 1987, Labrador basin: structural and stratigraphic style, *in* C. Beaumont and A.J. Tankard, eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists Memoir 12, p. 17-43.

Bally, A.W., 1982, Musings over sedimentary basin evolution: Philosophical Transactions of the Royal Society of London, Series A, v. 305, p. 325-338.

Bell, J.S., in press, Investigating stress regimes in sedimentary basins using information from oil industry wireline logs and drilling records, *in* A. Hurst, ed., Geological applications of wireline logs: Geological Society of London.

Bell, J.S., and D.I. Gough, 1979, Northeast-southwest compressive stress in Alberta, evidence from oil wells: Earth and Planetary Science Letters, v. 45, p. 475-482.

Bergerat, F., 1987, Stress fields in the European platform at the time of Africa-Eurasia collision: Tectonics, v. 6, p. 99-132.

Bergman, E.A., and S.C. Solomon, 1985, Earthquake source mechanisms from body-waveform inversion and intraplate tectonics in the northern Indian Ocean: Physics of Earth and Planetary Interiors, v. 40, p. 1-23.

Cloetingh, S., 1986, Intraplate stresses: a new tectonic mechanism for fluctuations of relative sea level: Geology, v. 14, p. 617-620.
Cloetingh, S., and F. Nieuwland, 1984, On the mechanics of lithospheric stretching and doming: a finite element analysis: Geologie en Mijnbouw, v. 63, p. 315-322.
Cloetingh, S., and R. Wortel, 1985, Regional stress field of the Indian plate: Geophysical Research Letters, v. 12, p. 77-80.
Cloetingh, S., and R. Wortel, 1986, Stress in the Indo-Australian plate: Tectonophysics, v. 132, p. 49-67.
Cloetingh, S., H. McQueen, and K. Lambeck, 1985, On a tectonic mechanism for regional sea level variations: Earth and Planetary Science Letters, v. 75, p. 157-166.
Cloetingh, S., H. Kooi, and W. Groenewoud, in press, Intraplate stresses and sedimentary basin evolution, *in* R.A. Price, ed., The origin and evolution of sedimentary basins and their energy and mineral resources: American Geophysical Union Geodynamics Series; Washington, D.C.
Embry, A.F., in press, A tectonic origin for depositional sequences in extensional basins—implications for basin modeling, *in* T.A. Cross, ed., Quantitative dynamic stratigraphy: Prentice Hall.
Given, M.M., 1977, Mesozoic and early Cenozoic geology of offshore Nova Scotia: Bulletin of Canadian Petroleum Geology, v. 25, p. 63-91.
Greenlee, S.M., F.W. Schroeder, and P.R. Vail, 1988, Seismic stratigraphy and geohistory of Tertiary strata from the continental shelf off New Jersey: calculation of eustatic fluctuations from stratigraphic data, *in* R.E. Sheridan and J.A. Grow, eds., The geology of North America, the Atlantic continental margin: Decade of North American Geology Series, Geological Society of America, v. I-2, p. 399-416.
Hallam, A., 1988, A reevaluation of Jurassic eustasy in the light of new data and the revised Exxon curve, *in* C.K. Wilgus et al., eds., Sea level changes: an integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 43, p. 261-274.
Haq, B.U., J. Hardenbol, and P.R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156-1167.
Houseman, G., and P. England, 1986, A dynamic model of lithosphere extension and sedimentary basin formation: Journal of Geophysical Research, v. 91, p. 719-729.
Hubbard, R.J., 1988, Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins: American Association of Petroleum Geologists Bulletin, v. 72, p. 49-72.
Jansa, L.F, F.M. Gradstein, I.M. Harris, W.A.M. Jenkins, and G.L. Williams, 1976, Stratigraphy of the Amoco-IOE Murre G-67 well, Grand Banks of Newfoundland: Geological Survey of Canada Paper 75-30, p. 1-14.
Johnson, B., and A.W. Bally (eds.), 1986, Intraplate deformation: characteristics, processes and causes: Tectonophysics, v. 132, p. 1-278.
Kent, D.V., and F.M. Gradstein, 1985, A Cretaceous and Jurassic geochronology: Geological Society of America Bulletin, v. 96, p. 1419-1427.
Klein, R.J., and M.V. Barr, 1986, Regional state of stress in western Europe, *in* O. Stephensson, ed., Rock stress and rock stress measurements: Lulea, Centek Publishers, p. 33-44.
Klitgord, K.D., and H. Schouten, 1986, Plate kinematics of the central Atlantic, *in* P.R. Vogt and B.E. Tucholke, eds., The geology of North America, the western North Atlantic region: Decade of North American Geology Series, Geological Society of America, v. M, p. 351-378.
Kominz, M.A., 1984, Oceanic ridge volumes and sea-level change—an error analysis, *in* J.S. Schlee, ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 109-127.
Kooi, H., and S. Cloetingh, 1989, Intraplate stresses and the tectono-stratigraphic evolution of the central North Sea, this volume.
Lambeck, K., S. Cloetingh, and H. McQueen, 1987, Intraplate stresses and apparent changes in sea level: the basins of northwestern Europe, *in* C. Beaumont and A.J. Tankard, eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists Memoir 12, p. 259-268.
Letouzey, J., 1986, Cenozoic paleo-stress pattern in the Alpine foreland and structural interpretation in a platform basin: Tectonophysics, v. 132, p. 215-231.
Livnat, A., A. Lifshitz, and A. Flexer, 1987, The tectonic style of the southern Arava rift margins, Israel: alternating stress fields in wrench-rifting processes: Tectonophysics, v. 141, p. 151-168.
Miall, A.D., 1986, Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record: American Association of Petroleum Geologists Bulletin, v. 70, p. 131-137.
Palmer, A.R., 1983, The Decade of North American Geology, 1983 geologic time scale: Geology, v. 11, p. 503-504.
Parkinson, N., and C. Summerhayes, 1985, Synchronous global sequence boundaries: American Association of Petroleum Geologists Bulletin, v. 69, p. 685-687.
Philip, H., 1987, Plio-Quaternary evolution of the stress field in Mediterranean zones of subduction and collision: Annales Geophysicae, v. 5B, p. 301-320.
Pitman, W.C., III, and X. Golovchenko, 1983, The effect of sea level change on the shelfedge and slope of passive margins, *in* D.J. Stanley and G.T. Moore, eds., The shelfbreak: critical interface on continental margins: Society of Economic Paleontologists and Mineralogists Special Publication 33, p. 41-58.
Poag, C.W., 1985, Geological evolution of the United States Atlantic continental margin: New York, Van Nostrand Reinhold, 383 p.
Pollitz, F.F., 1988, Episodic North America and Pacific plate motions: Tectonics, v. 7, p. 711-726.
Richardson, R.M., S.C. Solomon, and N.H. Sleep, 1979, Tectonic stress in the plates: Reviews of Geophysics and Space Physics, v. 17, p. 981-1019.
Schlanger, S.O., 1986, High-frequency sea-level oscillations in Cretaceous time: an emerging geophysical problem: American Geophysical Union Geodynamics Series, v. 15, p. 61-74.
Sleep, N.H., and N.S. Snell, 1976, Thermal contraction and flexure of mid-continent and Atlantic marginal basins: Geophysical Journal of the Royal Astronomical Society, v. 45, p. 125-154.
Srivastava, S.P., J. Verhoef, and R. Macnab, 1988, Results from a detailed aeromagnetic survey across the northeast Newfoundland margin, part II: Early opening of the North Atlantic between the British Isles and Newfoundland: Marine and Petroleum Geology, v. 5, p. 324-337.
Steckler, M.S., A.B. Watts, and J.R. Thorne, 1988, Subsidence and basin modeling at the U.S. Atlantic passive margin, *in* R.E. Sheridan and J.A. Grow, eds., The geology of North America, the Atlantic continental margin: Decade of North American Geology Series, Geological Society of America, v. I-2, p. 399-416.
Tankard, A.J., and H.J. Welsink, 1987, Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland: American Association of Petroleum Geologists Bulletin, v. 71, p. 1210-1232.
Tankard, A.J., and H.R. Balkwill, 1989, Extensional tectonics of the North Atlantic: introduction, this volume.
Tankard, A.J., and H.J. Welsink, 1989, Mesozoic extension and styles of basin formation in Atlantic Canada, this volume.
Tankard, A.J., H.J. Welsink, and W.A.M. Jenkins, 1989, Structural styles and stratigraphy of the Jeanne d'Arc basin, Grand Banks of Newfoundland, this volume.
Vail, P.R., R.M. Mitchum, and S. Thompson, 1977, Seismic stratigraphy and global changes of sea level, part 4: global cycles of relative changes of sea level, *in* C.E. Payton, ed., Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 83-97.
Watts, A.B., 1982, Tectonic subsidence, flexure and global changes of sea level: Nature, v. 297, p. 469-474.
Watts, A.B., and J.R. Thorne, 1984, Tectonics, global changes in sea level and their relationship to stratigraphical sequences at the U.S. Atlantic continental margin: Marine and Petroleum Geology, v. 1, p. 319-339.
Welsink, H.J., J.D. Dwyer, and R.J. Knight, 1989, Tectonostratigraphy of the passive margin off Nova Scotia, this volume.
Welsink, H.J., S.P. Srivastava, and A.J. Tankard, 1989, Basin architecture of the Newfoundland continental margin and relationship to ocean crust fabrics during extension, this volume.
Wortel, R., and S. Cloetingh, 1981, On the origin of the Cocos-Nazca

spreading center: Geology, v. 9, p. 425-430.
Wortel, R., and S. Cloetingh, 1983, A mechanism for fragmentation of oceanic plates, *in* J.S. Watkins and C.L. Drake, eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 793-801.
Ziegler, P.A., 1988, Evolution of the Arctic-North Atlantic and the western Tethys: American Association of Petroleum Geologists Memoir 43, 198 p.
Ziegler, P.A., 1989, Evolution of the North Atlantic: an overview, this volume.
Ziegler, P.A., and B. van Hoorn, 1989, Evolution of North Sea rift system, this volume.
Zoback, M.L., in press, The World Stress Map Project: Nature.
Zoback, M.L., S.P. Nishenko, R.M. Richardson, H.S. Hasegawa, and M.D. Zoback, 1986, Mid-plate stress, deformation, and seismicity, *in* P.R. Vogt and B.E. Tucholke, eds., The Geology of North America, the western North Atlantic region: Decade of North American Geology Series, Geological Society of America, v. M, p. 351-378.