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Plate reorganization: a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic?

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Abstract: Subsidence analysis of wells in the central North Sea and Labrador–Grand Banks and off the West Greenland, Scotian shelf and United States Atlantic margin shows distinct quantitative stratigraphic correlation patterns of circum North Atlantic sites. A significant departure from the overall decrease in subsidence for the Pliocene occurs in many wells, when the rate is found to have increased one or more orders of magnitude from Oligocence/Miocene rates. Wells were selected along transects from shore to basin to find if relative basin position is influenced by differential basin subsidence. Although stratigraphic resolution is not detailed, more basinward sites experienced up to four times larger subsidence rates in the late Neogene than in the Oligocene/Miocene, with a peak in the Pliocene. Wells at the basin edge experienced much less subsidence or showed uplift. The observations are consistent with a rapid change of intraplate stress at the cause for this observed transition in Neogene subsidence. Major reorganizations of spreading direction and rate occurred during the Pliocene along the entire Atlantic spreading system, possibly in conjunction with more global changes in plate motions. We propose that the associated changes in intraplate stress caused the excess margin subsidence. Relative uplift along basin edges is consistent with this mechanism of relative movement and may explain apparent eustatic changes in sea level.

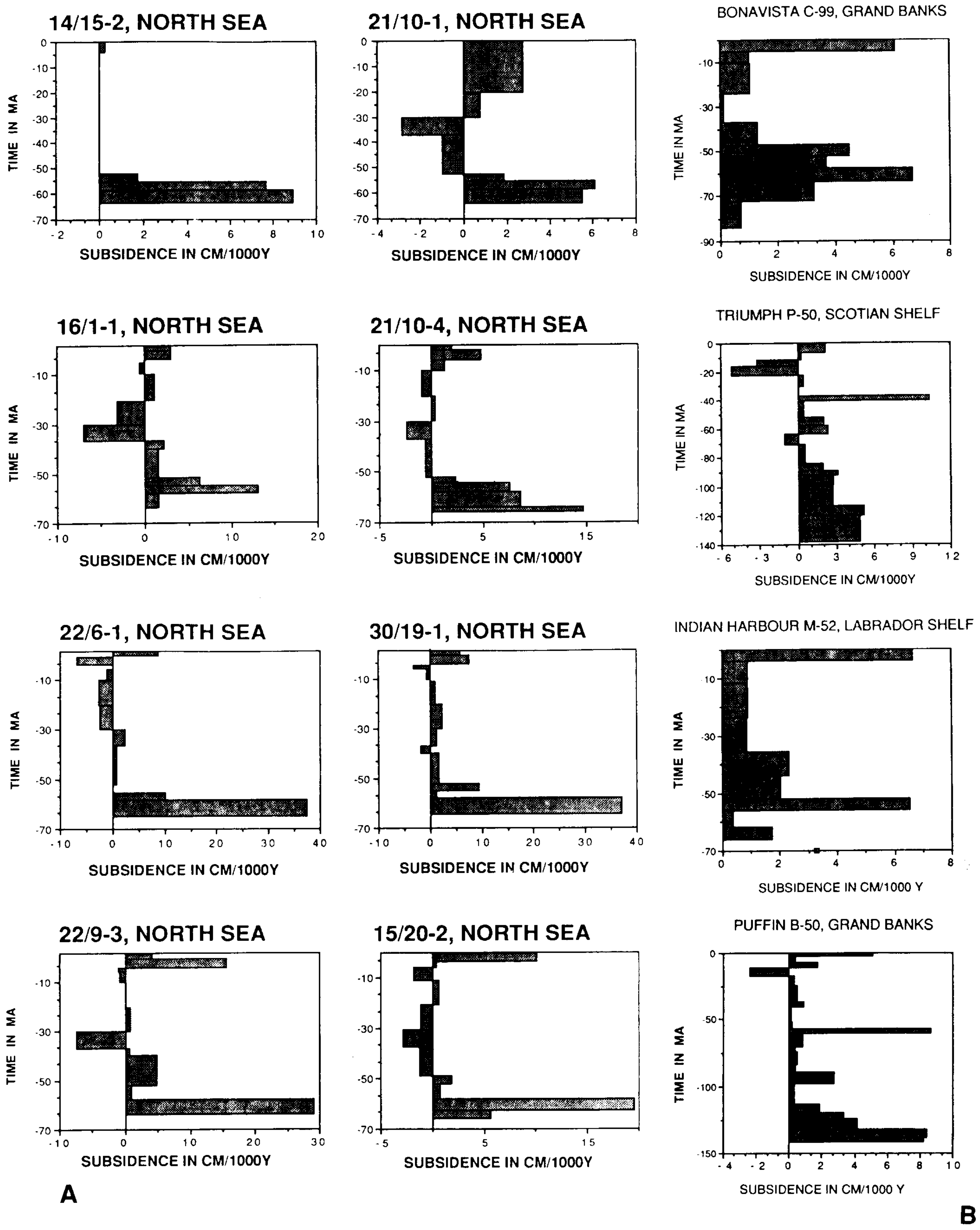
During the last few years thermal models of basin evolution (Sleep 1971; McKenzie 1978) have successfully explained many of the long-term features of basin subsidence. Short-term deviations from long-term basin subsidence have characteristically been attributed to short-term eustatic changes in sea level (Watts & Steckler 1979). Similarly, Vail and colleagues (e.g. Haq *et al.* 1987) invoke glaciation to explain sea-level lowerings even in case of little or no terrestrial record, as for example during Cretaceous time. More recently, it has been shown that such short-term changes in relative sea level can equally well be caused by rapid, stress-induced vertical motions of the lithosphere within sedimentary basins (Cloetingh *et al.* 1985; Cloetingh 1986; Lambeck *et al.* 1987). This work showed that apart from being important in the formation of rifted basins intraplate stresses also play a critical role during their subsequent subsidence history. The ongoing World Stress Map Project has convincingly established the existence of large-scale consistently oriented stress patterns in the lithosphere (Zoback *et al.* 1989), with recent compelling evidence for changes in the magnitudes and orientations of these stress fields on time scales of a few Ma (Philip 1987; Bergerat 1987; Letouzey 1986) in association with collision and rifting processes in the lithosphere. A number of stratigraphic criteria have been developed to discriminate between the effects of stress-induced and eustatic contributions to the stratigraphic record as successfully applied to the Canadian Sverdrup Basin (Embry 1989).

We present the results of subsidence analysis of wells at locations along the Atlantic margin of the United States, the Scotian Basin, the Labrador–Grand Banks, the Western Greenland margin and the North Sea, which together show a simultaneously occurring rapid late Neogene subsidence phase around the northern Atlantic. We show that the duration and character of this tectonic subsidence phase deviates from predictions of standard thermal models of

Table 1. *Listing of exploration well sites, circum North Atlantic, at depth intervals (shown as maximum depth analysed) used for subsidence analysis*

US Atlantic margin		
COST GE–1	Georgia Embayment	2252 m B
COST B3	Baltimore Canyon	4269 m
COST B2	Baltimore Canyon	3606 m
Canadian Atlantic margin		
Triumph 8–50	Scotian shelf	15043 ft
Mohican I100	Scotian shelf	14414 ft
Puffin B90	Grand Banks	4701 m
Blue H28	Grand Banks	5191 m B
Bonavista C99	Grand Banks	3670 m B
Karlsefni H13	Labrador shelf	13546 m B
Indian Harbour	Labrador shelf	10686 m B
Northwest Greenland margin		
Kangamiut-1		3700 m B
Ikermiut-1		2814 m
Nukik-1		2395 m
Central North Sea, Central Graben, UK sector		
30/19-1		3352 m
22/9-3		2865 m
22/6-1		2994 m
21/10-1		2432 m
21/10-4		2808 m
16/1-1 (Norwegian sector)		2750 m
15/20-2		2343 m
14/15-2		1900 m

Symbol B denotes wells drilled into basement rocks.


14/15-2, NORTH SEA

21/10-1, NORTH SEA

BONAVISTA C-99, GRAND BANKS

16/1-1, NORTH SEA

21/10-4, NORTH SEA

TRIUMPH P-50, SCOTIAN SHELF

22/6-1, NORTH SEA

30/19-1, NORTH SEA

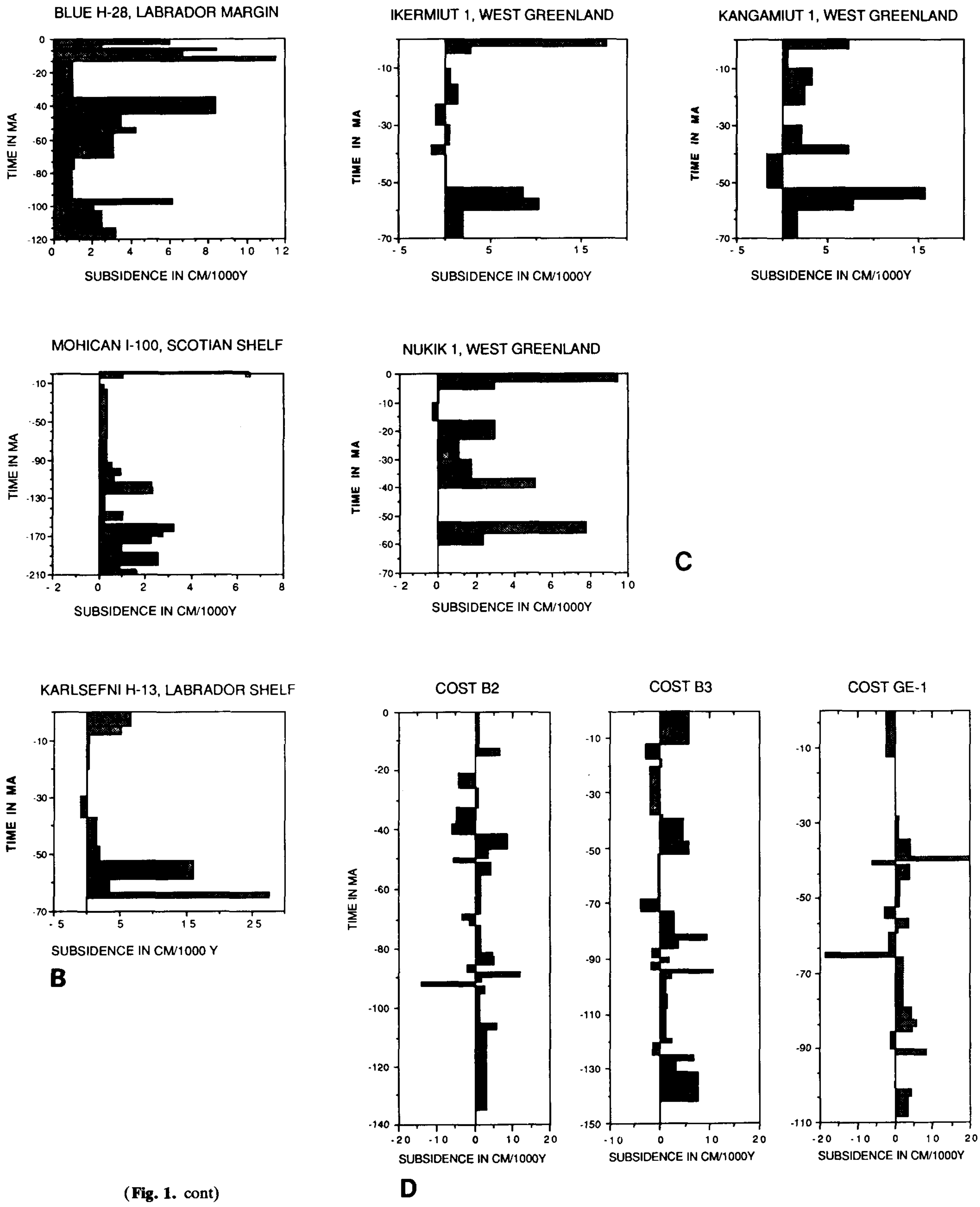
INDIAN HARBOUR M-52, LABRADOR SHELF

22/9-3, NORTH SEA

15/20-2, NORTH SEA

PUFFIN B-50, GRAND BANKS

Fig. 1. Observed tectonic subsidence in well sites around the northern Atlantic. Histograms show extremely high subsidence and sedimentation rates for the late Neogene for most wells. (**A**) Central North Sea Graben, U.K. sector. (**B**) Canadian Atlantic margin. (**C**) Northwest Greenland margin. (**D**) US Atlantic margin.


BLUE H-28, LABRADOR MARGIN
TIME IN MA
0
-20
-40
-60
-80
-100
-120
0
2
4
6
8
10
12
SUBSIDENCE IN CM/1000Y
IKERMIUT 1, WEST GREENLAND
TIME IN MA
-10
-30
-50
-70
-5
5
15
SUBSIDENCE IN CM/1000Y
KANGAMIUT 1, WEST GREENLAND
TIME IN MA
-10
-30
-50
-70
-5
5
15
SUBSIDENCE IN CM/1000Y
MOHICAN I-100, SCOTIAN SHELF
TIME IN MA
-10
-50
-90
-130
-170
-210
-2
0
2
4
6
8
SUBSIDENCE IN CM/1000Y
NUKIK 1, WEST GREENLAND
TIME IN MA
0
-10
-20
-30
-40
-50
-60
-70
-2
0
2
4
6
8
10
SUBSIDENCE IN CM/1000Y
C
KARLSEFNI H-13, LABRADOR SHELF
TIME IN MA
-10
-30
-50
-70
-5
5
15
25
SUBSIDENCE IN CM/1000 Y
B
COST B2
TIME IN MA
0
-20
-40
-60
-80
-100
-120
-140
-20
-10
0
10
20
SUBSIDENCE IN CM/1000Y
COST B3
-10
-30
-50
-70
-90
-110
-130
-150
-10
0
10
20
SUBSIDENCE IN CM/1000Y
COST GE-1
-10
-30
-50
-70
-90
-110
-20
-10
0
10
20
SUBSIDENCE IN CM/1000Y
D

(**Fig. 1.** cont)

basin evolution. We propose that the late Neogene phase of rapid basin subsidence in the northern Atlantic is caused by plate reorganization and associated changes in the intraplate stress fields.

Late Neogene subsidence around the North Atlantic

The 21 wells analysed in this study are listed in Table 1. These well sections form part of a much larger data set involving over 85 wells, analysed by one of us (FMG) for circum Atlantic stratigraphy and bathymetry. Figure 1 gives the observed tectonic subsidence for the wells in Table 1. Histograms show a general pattern of rapid late Neogene subsidence, preceded by a phase of quiescence in the subsidence record. This phase of late-stage rapid subsidence cannot be explained by thermal models which predict decreasing subsidence with age after formation of the basin (e.g. McKenzie 1978; Sclater & Christie 1980). The subsidence analysis shows that although contributing to the late Neogene subsidence, changes in palaeobathymetry do not suffice to cause the rapid subsidence. Figures 2a and 2b show the position of two long seismic lines connecting Grand Banks wells and the central North Sea wells listed in Table 1. The COST GE-1 well, located on the inner shelf, deviates from the general trend of rapid excess subsidence by showing a late Neogene phase of uplift (see also Heller *et al.* 1982).

Rates of tectonic subsidence in the wells were analysed using methods developed by Stam *et al.* (1987). We have included the effects of changes in water depth and of long-term eustatic changes in sea level. Short-term apparent sea-level changes may be detected in the calculated

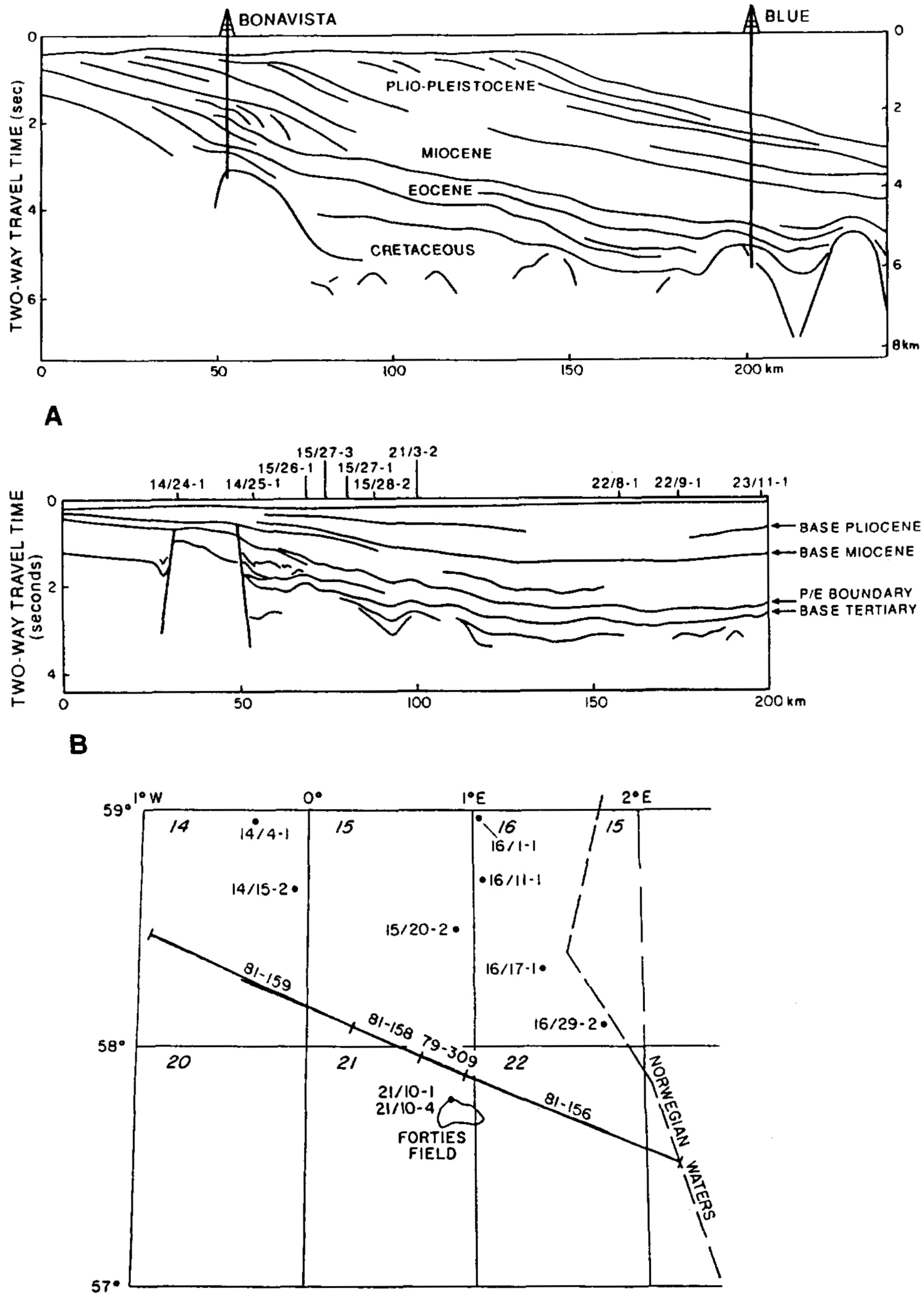


Fig. 2. Seismic cross sections displaying large thicknesses of late Neogene sequences around the northern Atlantic. (**A**) Seismic line across the eastern margin of Canada from Bonavista to Blue. (**B**) Seismic line through the central North Sea Graben, U.K. sector (14/15-2 to 21/10-4). Position of some wells listed in Table 1 is indicated.

subsidence trends as local and short-term deviations. The standard Cenozoic timescale follows Berggren *et al.* (1986), whereas the Mesozoic scale is based on Kent & Gradstein (1985). For decompaction of lithological units in the wells use was made of porosity-depth trends from porosity measurements and from sonic log data for shale, siltstone, sandstone and limestone. Where no porosity-depth or sonic velocity-depth data were available, as in the North Sea and West Greenland wells, use was made of default decompaction equations slightly modified after Baldwin & Butler (1985). The equations include corrections for undercompacted shales, commonly encountered when shale thickness exceeds 200 m or more. Although lithospheric flexure plays an important role in basement response to applied loads, we adopt local isostasy in the backstripping procedure. This assumption is reasonable for our investigation of short-term changes in tectonic subsidence as the influence of finite lithospheric strength affects primarily long-term patterns of basin subsidence (Watts *et al.* 1982). This is of minor importance for analysis of short-term subsidence changes in the Neogene, as the characteristics of short-term eustatic or tectonic components in the subsidence record are largely unaffected by assumptions on the isostatic response of the lithosphere.

Biostratigraphy and palaeoecology

Age versus depth interpretations for the majority of well sites is based on quantitative foraminiferal zonations for the Labrador shelf and central North Sea (Gradstein *et al.* 1985, 1988). The stratigraphy of the West Greenland offshore sites follows dinoflagellate zonations compiled by Toxwenius (1986). US COST wells stratigraphy is after Scholle (1977, 1980, 1982). With a few exceptions (e.g. Mohican I100 and Blue H81 wells which have a deep marine planktonic record), late Neogene stratigraphic resolution is limited, the result of shallow marine, terrigeneous clastic conditions and high-latitude climatic influences. In general the following Cenozoic stratigraphic levels may be distinguished: Pleistocene, mid-Pliocene, lower Pliocene, upper Miocene, middle Miocene, upper Oligocene–lower Miocene, lower Oligocene (Rupelian), upper Eocene, middle Eocene, lower Eocene (Ypresian), the Palaeocene–Eocene boundary, upper Palaeocene (Selandian), lower Palaeocene (Danian) and upper Maastrichtian. The resolution is sufficient to deduce significant changes in subsidence rate over 2 to 3 Ma.

A critical parameter for subsidence and burial analysis is water depth. Six basic categories are recognized, classified according to both water depth and distance from shore.

(1) Non marine, terrestrial; spores and pollen, no foraminifers.

(2) Shallow neritic; comprises marginal marine to inner shelf sediments laid down in water less than 100 m deep; diagnostic foraminiferal assemblages are of low generic and species diversity, with rare or no planktonic forms. Upper Neogene sections generally fall in this category, with *Cibicidoides, Elphidium, Cassidulina, Bulimina, Melonis, Quinqueloculina* and gastropods and bryozoans.

(3) Deep neritic; comprises sediments laid down in water depth of between approximately 100 and 200 m. Foraminiferal generic and species diversity varies, planktonic forms occur locally in low abundance. Among the Neogene benthonic genera occur *Uvigerina, Pullenia, Gyroidina, Alabamina, Sphaeroidina, Fursenkoina, Sigmoilopsis, Spiroplectammina* (of the *carinata* type) and *Ceratobulimina*. Palaeogene assemblages reflect a Midway type fauna.

(4) Upper bathyal (upper slope); comprises sediments laid down in water depths of 200–750 m. Foraminiferal generic and species diversity is high. In the North Sea, Labrador and northern Grand Banks the assemblages may be dominated by coarse, often large-sized agglutinated taxa, including some cyclamminids and tubular forms. In more basinward wells planktonic taxa may occur frequently (mostly turborotaliid and globigennirid taxa), together with radiolarians.

(5) Middle bathyal (middle slope); comprises sediments laid down in water depths of 750–1000 m, or slightly deeper than 1000 m. Foraminiferal diversity is high; calcareous benthonic forms include *Cibicidoides wuellerstorfi, Melonis pompiloides* and *Uvigerina rustica,* all of Neogene age, and *Pleurostomella, Osangularia, Stilostomella* and *Nuttalides,* all Palaeogene in age. Agglutinated benthonic assemblages are diverse and contain both coarse and finer grained, smaller sized taxa, particularly *Cystammina, Rzehakina* and *Labrospira* (always rare). With few exceptions, as in the Blue H81 well drilled in 1470 m of water on the Grand Banks, well sites are bathyal in the Palaeogene and neritic in the Neogene, largely becoming inner neritic in the late Neogene.

Effect of late stage compression on subsidence and stratigraphy

Intraplate stresses modulate the basin deflection caused by thermal subsidence and induce differential vertical motions of a sign and magnitude that depend on the position within the basin (Cloetingh *et al.* 1985; see Fig. 3). Intraplate compression causes relative uplift of the basin flank, subsidence at the basin centre, and seaward migration of the shoreline. As a result, an offlap develops and an unconformity is produced. Increases in the level of tensional stress induce widening of the basin, lower the flanks and cause landward migration of the shoreline, producing a rapid onlap phase.

Stress-induced differential vertical motions within sedimentary basins have also important consequences for the dynamics of erosion and sedimentation. For example, the compression-induced uplift at the basin flank is accompanied by enhanced erosion of the uplifted area and increased sedimentation in the basin centre (Fig. 4). On the other hand, a decrease in sedimentation might also occur when the uplifted area induces significant changes in the drainage pattern of the hinterland. Stress-induced uplift at the basin flank changes the geometry of source and sinks of sediments. Significant distortion of the basin shape at the flanks of passive margins during plate reorganizations could also give rise to changes in water-circulation such as that documented by Dillon & Popenoe (1988) for the US Atlantic margin, with possible consequences for climatic change.

The magnitude of the stress-induced vertical movements in a basin is strongly rheology dependent. To investigate the effects of depth-dependent rheology we constructed a model for oceanic lithosphere based on extrapolation of rock mechanics data (Goetze & Evans 1979), adopting a strain rate $\dot{\varepsilon} = 10^{-18}\,\mathrm{s}^{-1}$, characteristic for flexural post-rift sedimentary basin evolution. A tenfold increase in the strain rate, during for example periods of active stretching,

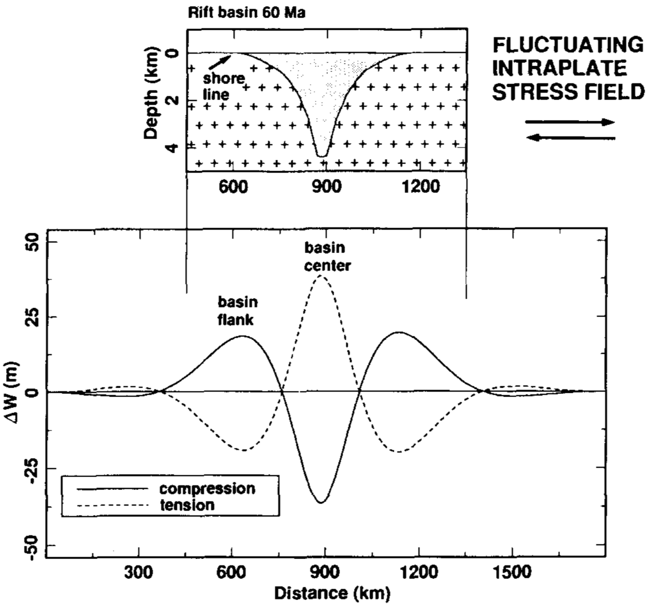


Fig. 3. Flexural deflections at a sedimentary basin caused by changes in the level of intraplate stress. Sign convention: uplift is positive, subsidence is negative. Above: a 60 Ma old rifted basin formed by stretching. The sediments flexurally load an elastic plate. The thickness of this plate varies horizontally due to lateral changes in the temperature structure of the lithosphere. Below: the vertical deflections induced by a change to 1 kbar compression (solid curve). The flank of the basin is uplifted and the basin centre subsides. A change to 1 kbar tension (dashed curve) induces uplift at the basin centre and subsidence at the basin flank. The shape and magnitude of these stress-induced deflections evolve through time not only because of the increasing load, but also due to changes in the thermal structure of the lithosphere. After Cloetingh *et al.* 1985.

changes the thickness of the mechanically strong part of the lithosphere with only a few kilometres (e.g. Goetze & Evans 1979). This particular model combines brittle deformation in the upper lithosphere with temperature-dependent ductile deformation in deeper parts of the lithosphere. The total integrated strength of the plate, controlled by the thermal structure of the lithosphere, increases with age. Figure 5 displays subsidence through time in the centre of two 100 Ma old basins for a uniform elastic plate model and an oceanic depth-dependent rheology model, respectively. The solid curves show the stress-induced deviation from thermal subsidence for compressional stress levels that linearly increase from 90 Ma onward to values of up to $30 \times 10^{12}\,\mathrm{Nm}^{-1}$. Inspection of Fig. 5 demonstrates that late-stage compression can give rise to a significant increase in subsidence rates, especially for realistic rheologies with a finite strength of the lithosphere. The stretching formalism (McKenzie 1978) attributes basin subsidence solely to the events during basin formation. Ignorance of late-stage compression can, therefore, also give rise to significant overestimates (up to approximately 15%) in β values (the amount of crustal thinning) derived from subsidence analysis (see also Kooi & Cloetingh 1989*b*). Still, the estimates for stress-induced vertical motions of the lithosphere displayed in Fig. 5 are rather conservative. Rheological models indicate that continental lithosphere can be substantially weaker than oceanic lithosphere (Barton & Wood 1984; Stephenson *et al.* 1987). A specific change in intraplate stress will, therefore, induce larger vertical motions in rifted basins (like the North Sea) located on continental lithosphere than the predictions given for oceanic lithosphere.

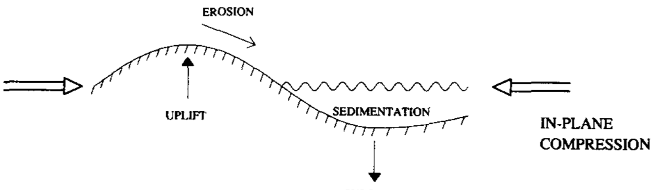


Fig. 4. Compression-induced changes in sedimentation and erosion patterns at the centre and flank of sedimentary basins on flexed lithosphere.

Modelling of the stratigraphy of the US Atlantic margin (Cloetingh *et al.* 1989) and the North Sea (Lambeck *et al.* 1987; Kooi & Cloetingh 1989*a*) has shown that the stratigraphy can be successfully simulated by a stress field in which magnitude fluctuates through time superimposed on the long-term thermal evolution. The inferred palaeo-stress was found to be largely consistent with independent data sets on the kinematic (Klitgord & Schouten 1986) and tectonic evolution (Letouzey 1986; Ziegler & Van Hoorn 1989) of the northern Atlantic, with a tensional stress field during Mesozoic times followed by a compressional stress field during the Tertiary where the magnitude increases with age.

We similarly model numerically the stratigraphic record of the Orphan Basin (northern Grand Banks; see Fig. 6). Faunal analyses of the Bonavista C99 and Blue H81 wells provided water depth information. In the present modelling we concentrate on the Cenozoic stratigraphy. Special attention is given to the conspicuous great thickness of late Neogene strata and the contemporaneous narrowing of the basin, phenomena which are also observed in the seismic section from the North Sea (Fig. 2b).

Figure 7 shows the modelled stratigraphy of the Orphan Basin using a two-layer stretching model (Royden & Keen 1980). We have employed two rifting phases of finite duration; Callovian–Aptian (163–115 Ma; Tankard & Welsink 1987) and Late Cretaceous (98–65 Ma; Keen *et al.* 1987). This suggests that stretching persisted after the North America–Europe breakup at about 80 Ma (Srivastava 1978). Keen *et al.* (1987) even adopted a stretching phase at 55 Ma and related this late phase of extension to continent–continent transform motion along the Charlie Fracture Zone. We have used crustal stretching factors δ up to a maximum of 1.45 for the Early Cretaceous and 1.53 for the Late Cretaceous rifting episodes, respectively. However, during the former the locus of highest crustal stretching is situated landward of the Blue well and during the latter rifting phase seaward of this well. Inspection of palaeobathymetry data shows that the relative absence of Late Cretaceous sediments in the Orphan Basin cannot solely be attributed to sediment starvation in a strongly subsiding basin. Rapid Late Cretaceous syn-rift subsidence must therefore have been largely counteracted by isostatic rebound forces induced by the relatively shallow level of lithospheric necking (Braun & Beaumont 1989) and/or by additional heat input into the lithosphere, which cannot be explained by uniform stretching. For reasons of convenience we adopted the latter possibility and used subcrustal

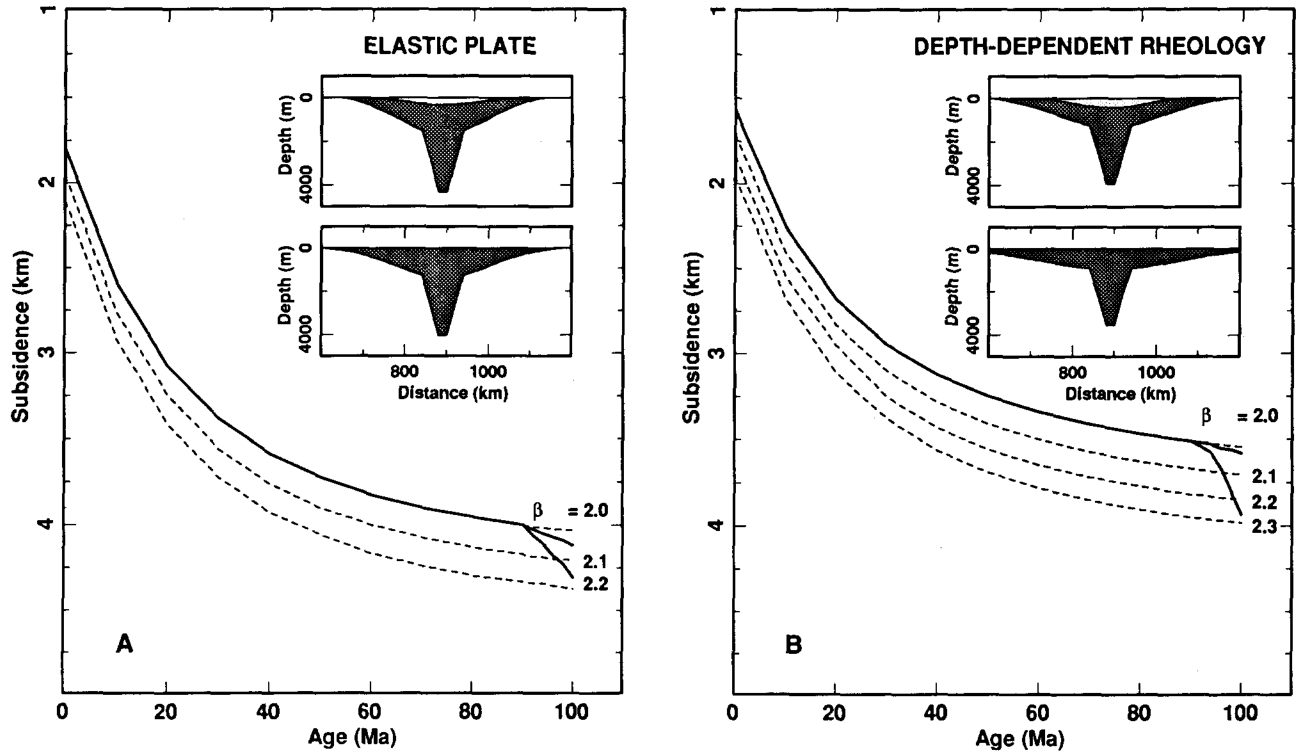


Fig. 5. Sediment accumulation through time at the centre of a 100 Ma old sedimentary basin. (**A**) Subsidence calculated for an elastic plate model for the mechanical properties of the lithosphere. (**B**) Subsidence calculated for an oceanic depth-dependent rheological model based on extrapolation of rock-mechanics data (Goetze & Evans 1978). The solid lines indicate sediment accumulation for increasing intraplate compressive stress levels from 90 Ma onward up to 10 and $30 \times 10^{12}\,\mathrm{Nm}^{-1}$ for the upper and lower curve, respectively. Dashed lines denote subsidence in the absence of intraplate stresses for different β values in the centre of the basin. Upper and lower panels in the insets show steershead geometry of the rifted basin at a timing just before (90 Ma) and after the phase of late-stage compression (100 Ma). Dark shading denotes the sediment accumulation associated with stretching and long-term cooling of the lithosphere. Light shading indicates the wedge of sediments filling the depression caused by a phase of late-stage compression.

attenuation factors β somewhat higher than crustal stretching δ for the Late Cretaceous rifting phase. This phase of high heat input into the lithosphere coincides with Senonian igneous activity that culminated during the Palaeocene in a major volcanic surge (Thulean volcanism) that affected much of the Arctic–North Atlantic borderlands (Ziegler & Van Hoorn 1989). The stretching factors used in this study are roughly in accordance with findings from Keen *et al.* (1987) who derived stretching factors from the combined analysis of well data and seismic data from Lithoprobe studies.

Figure 7 demonstrates that the overall characteristics of the late Neogene stratigraphy of the Orphan Basin can be reproduced by both maintaining the imposed palaeobathymetry information and increasing the level of intraplate compression. A late Neogene increase in compressive stress level of $1.17 \times 10^{13}\,\mathrm{Nm}^{-1}$ (roughly equivalent to 3 kbar in a 40 km thick elastic plate) induces a late Neogene phase of rapid basin narrowing and increase in tectonic subsidence of about 150 m, reproducing the order of magnitude of the observed acceleration in subsidence. Stress levels of this order of magnitude can be induced by plate tectonic forces during times of plate reorganization (e.g. Cloetingh & Wortel 1985) and have been shown to be capable of producing large-scale lithospheric buckling in old oceanic lithosphere in the northeastern Indian Ocean (Stein *et al.* 1989). These studies demonstrate that the folds in the lithosphere of the northeastern Indian Ocean require stress levels of the order of 5–6 kbar, equivalent to levels of in-plane force of $30 \times 10^{12}\,\mathrm{Nm}^{-1}$ (Stein *et al.* 1989; McAdoo & Sandwell 1985). A striking feature that appears from the study of the Indian Ocean stress field and similar work carried out in the framework of the World Stress Map Project on stresses in other lithospheric plates (Zoback *et al.* 1989) is that actual stress levels depend strongly on the specific geodynamic situation of the particular lithospheric plate. Note, however, that a brittle-ductile behaviour of the lithosphere drastically lowers the stress level inferred from the predictions of an elastic model for the lithosphere. As demonstrated in Fig. 5 this stress level is very much dependent on the actual rheology of the lithosphere beneath the basin and probably provides an upper limit for the stress levels expected to cause rapid differential motions in rheologically stratified continental lithosphere.

Discussion and conclusions

The detailed analysis of stratigraphic and palaeobathymetric data from wells at locations along the US Atlantic margin, the Scotian Basin, the Labrador/Grand Banks, the Western Greenland margin and the North Sea described in this paper demonstrates a simultaneously occurring, rapid, late Neogene subsidence phase around the northern Atlantic. The duration and character of the tectonic subsidence phase

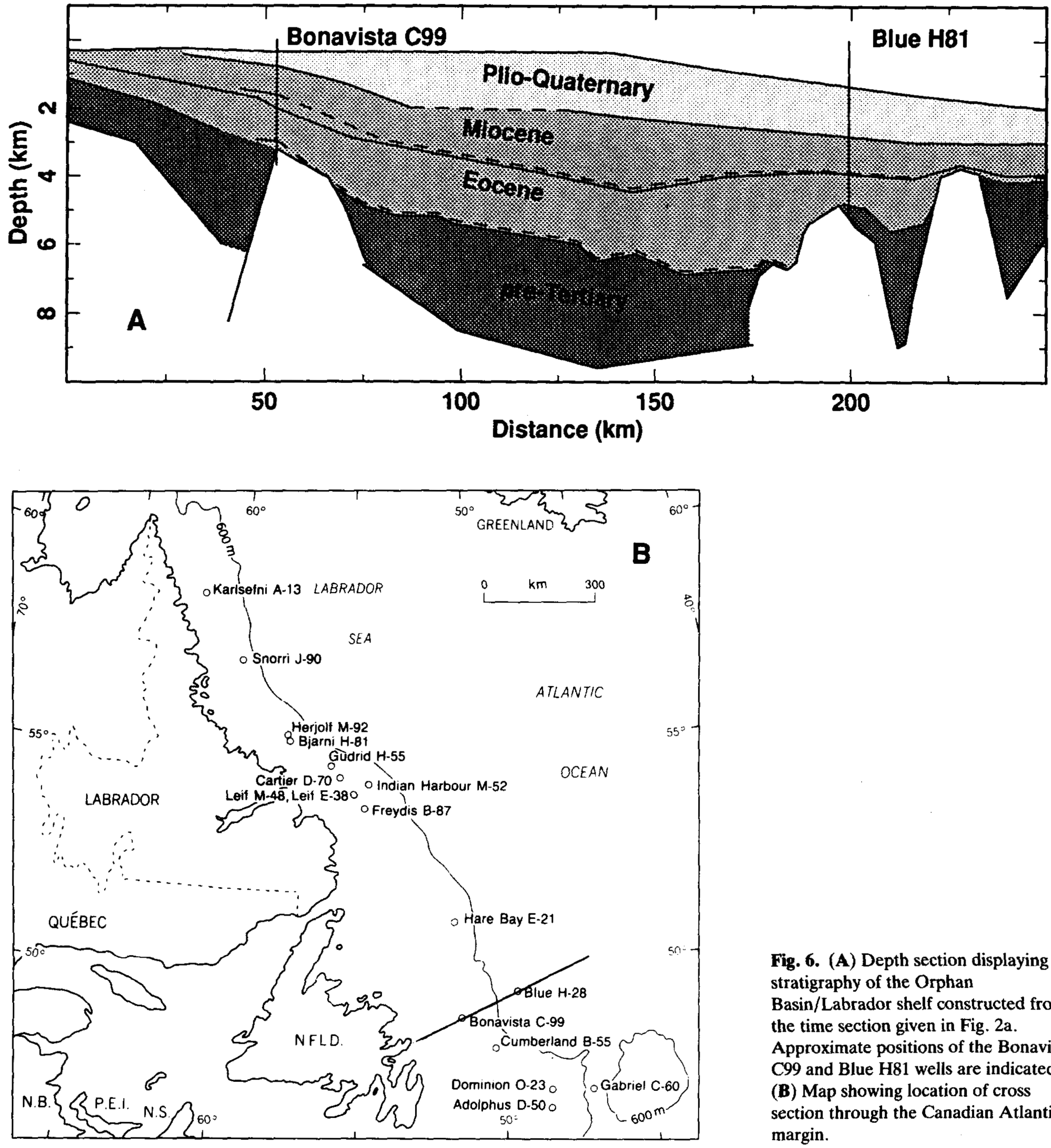


Fig. 6. (**A**) Depth section displaying stratigraphy of the Orphan Basin/Labrador shelf constructed from the time section given in Fig. 2a. Approximate positions of the Bonavista C99 and Blue H81 wells are indicated (**B**) Map showing location of cross section through the Canadian Atlantic margin.

cannot be explained by standard thermal models for basin evolution. We propose that the late Neogene phase of basin evolution is caused by plate reorganization and associated stress changes. Numerical modelling of this phenomenon for the Orphan Basin on Grand Banks, Nova Scotia shows that this short-term deviation in tectonic subsidence can be explained by a late Neogene increase in compressive intraplate stress.

Stretching models have, to a large extent successfully, been used by many workers as an explanation for the succession of rapid initial subsidence phases followed by a long-term phase of steady subsidence due to cooling of the lithosphere (e.g. Sclater & Celerier 1987). Short-term deviations of modest magnitude (of the order of a few tens up to a hundred metres or so) from the long-term patterns of thermal subsidence have been attributed to sea-level fluctuations (Watts & Steckler 1979). Similarly, short-term deviations of a magnitude too large to attribute to sea-level changes are often explained in terms of repeated phases of stretching (e.g. Greenlee *et al.* 1988). In previous work (Cloetingh *et al.* 1985, 1989; Cloetingh 1986) we have shown that modest fluctuations in intraplate stress levels can

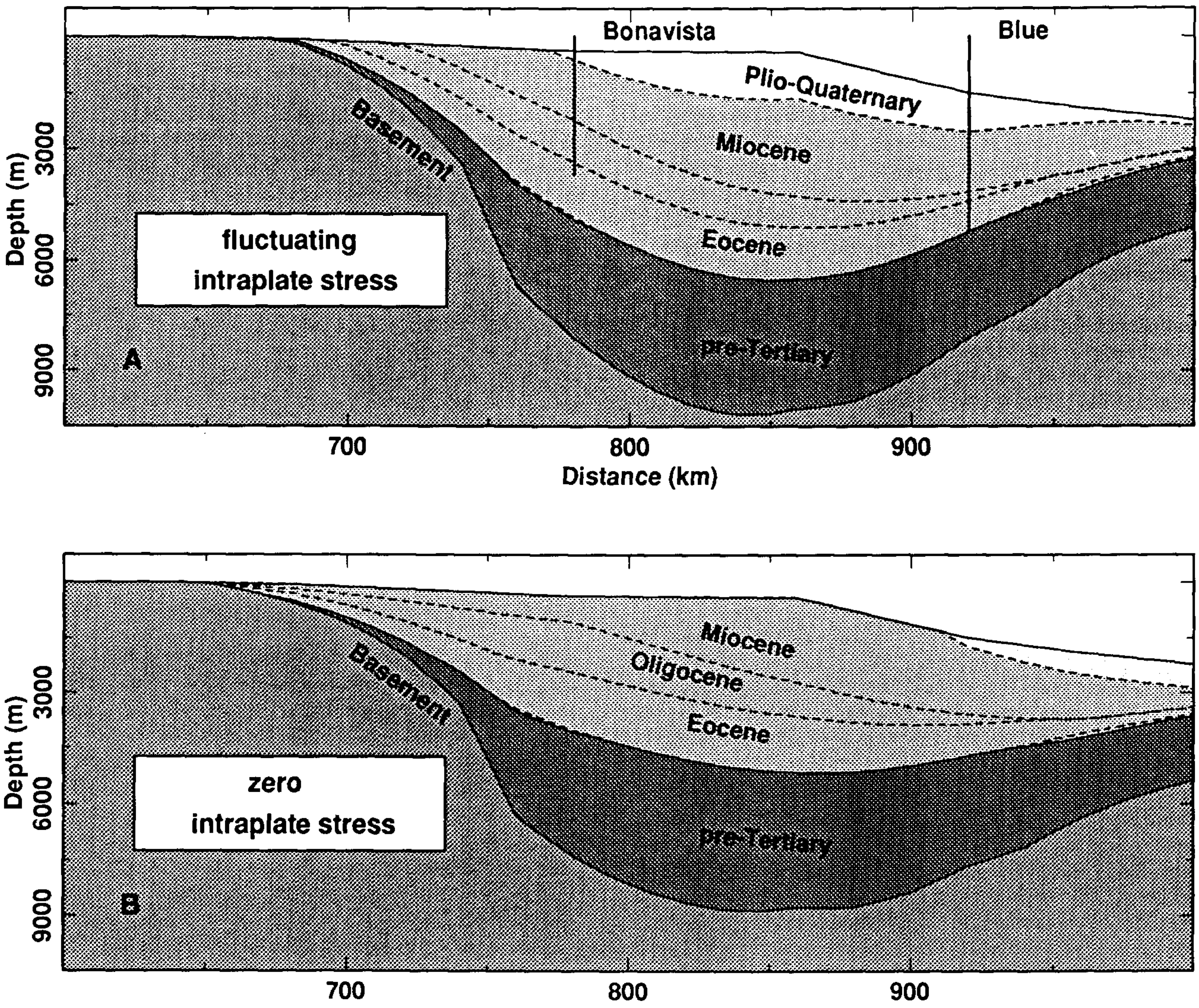


Fig. 7. Modelled stratigraphy of the Orphan Basin/Labrador shelf, employing a stretching model for basin formation. (**A**) Modelled stratigraphy incorporating a Plio–Quaternary increase in compressive stress level of 1.17×10^{13} Nm^{-1} in the analysis. Note the deepening and narrowing of the basin induced by late-stage compression. (**B**) Stratigraphy modelled in the absence of a fluctuating intraplate stress field.

produce vertical motions of the lithosphere of a rate and magnitude similar to Vail's third order cycles in apparent sea level. In the present paper, we have demonstrated that rapid accelerations in basin subsidence can equally well be produced by an increase in the level of intraplate compression of more substantial magnitude. This explanation has quite important implications for the thermal regime in sedimentary basins, in particular for the depth extent of the hydrocarbon window (Kooi & Cloetingh 1989*b*). Late-stage compression is obviously more plausible than a renewed phase of crustal stretching in the basins around the Atlantic, as both the present day and late Neogene stress field in these basins are of compressional character (Klein & Barr 1986; Zoback *et al.* 1989; Philip 1987).

Another interesting and well documented case of a rifted basin with a strong phase of late Neogene subsidence and which deviates from predictions from the stretching model is the Gulf de Lions passive margin in the northwestern Mediterranean. A detailed study of the Gulf de Lions margin by the Institut Francais du Petrole has revealed a strong excess subsidence in the basin centre, starting after 5 Ma, while simultaneously rapid uplift has occurred at the basin flanks (Burrus *et al.* 1987). As pointed out by Burrus *et al.* (1987), this rapid differential motion across the Gulf de Lions passive margin deviates from predictions of thermal models and coincides with a documented tectonic compressional phase. Stratigraphic modelling (Cloetingh *et al.* 1989) has established that an increase in intraplate compression can explain the observed subsidence patterns.

The orientations of both the present day stress field (Klein & Barr 1986) and the palaeo-stress fields (Letouzey 1986; Bergerat 1987) in NW Europe are in agreement with predictions derived from plate-motion models for northern Atlantic ridge-push forces and Africa–Europe convergence. These findings suggest a strong coupling between the plates surrounding the northern Atlantic. There are, for example, several striking observations that corroborate such a coupling between the late Neogene tectonics of the Mediterranean collisional events and the intraplate tectonic evolution of the northwestern European platform. Rapid accelerations in subsidence occur simultaneously over larger areas in the western Mediterranean (Burrus *et al.* 1987; Malinverno & Ryan 1986), the central Mediterranean and the Gulf of Suez (Evans 1986) and the eastern Mediterranean (Meulenkamp & Hilgen 1986). These events occur in association with distinct phases in the tectonic evolution of the ongoing collision between the Eurasian plate and the African plate. The culmination in tectonic activity at late Neogene times appears to a large extent to be controlled by the dynamics of the downgoing lithosphere in the Mediterranean collision zones. Similarly, discrete phases and peaks in compressional activity have been documented during Neogene times in the Bitlis suture zone and in the Zagros collision (e.g. Dewey & Sengor 1979), whereas the onset of a dramatic phase of lithospheric buckling in the northeastern Indian Ocean has been dated recently at 6–7 Ma (Cochran *et al.* 1987). Both the strike and wavelength of the folds induced by the collision of the Indian plate with the Eurasian plate are in agreement with stress data and stress models for the present day Indian plate. These studies demonstrate that the folds in the lithosphere of the northeastern Indian Ocean require stress levels of the order of 5–6 kbar (Stein *et al.* 1989).

A prominent reorganization of spreading directions and rates occurred at 2.5 Ma along the entire Atlantic spreading centre (Klitgord & Schouten 1986). Important tectonic phases during late Neogene time also occur on the western side of the Atlantic Ocean. A climax in compressional tectonics in the Arctic of northern Alaska and northern Canada has occurred at a timing of about 6 Ma, possibly connected with the formation of an incipient convergent plate boundary (Hubbard *et al.* 1987). Similarly, the termination of extension in the Basin and Range province during Pliocene times and the transition to epeirogenetic uplift of the Rocky Mountains and Great Plains are reflected in the record of vertical motions along the margins of the Gulf of Mexico (Galloway 1987; Hay *et al.* 1989). Episodicity in plate motions and associated changes in the Pacific and Atlantic plates in upper Miocene (9 Ma) and Pliocene (4 Ma) times have been documented in great detail recently by Pollitz (1986, 1988). His study further supports a causal link between late Neogene plate motion changes in the Pacific and Atlantic Oceans. As pointed out by Pollitz (1988), the timing of the plate motion changes is consistent with several features of the late Neogene geological history of northern America and tectonics along a large portion of both the eastern and western boundaries of North America. Examples include a correlation of the 9 Ma event with rifting in the western United States and intense compressional deformation along the northern Caribbean plate boundary. His analysis shows that the causes of the Pacific and northern American changes in plate motion are related to plate driving forces originating in the northwestern Pacific subduction zones.

Stress fields can be propagated over long distances (e.g. Letouzey 1986; Ziegler & Van Hoorn 1989) and so give the appearance of 'global changes'. That is any major change in the NE Atlantic or the Gulf of Mexico/Caribbean can effect the NW Atlantic. Major changes in plate trajectories might have had an effect on the world wide stress field (e.g. Pollitz 1988), especially on those regions where stresses are high and close to lithospheric failure. The interaction of rigid plates implies that important tectonic phases will be inter-regional and approximately synchronous. Tectonism and sedimentary response commonly will, however, show some time shifts from place to place (e.g. Hubbard 1988).

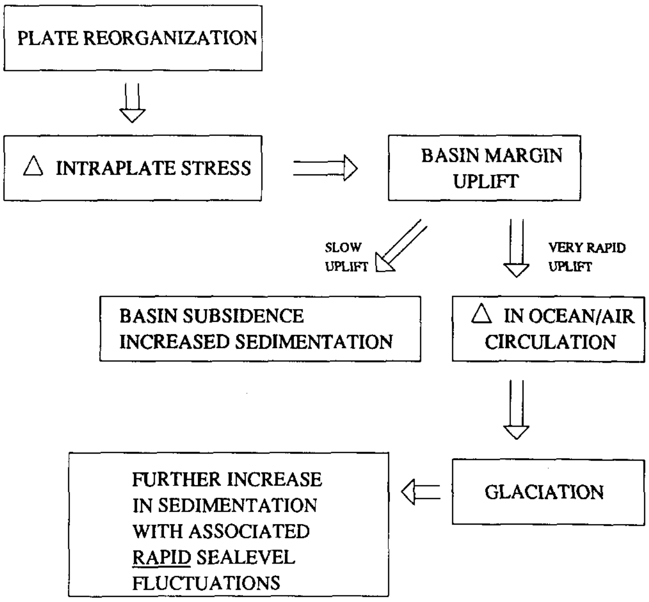


Fig. 8. Schematic diagram illustrating proposed relations between tectonics, basin subsidence and the record of sea-level changes.

The present study strongly suggests that the rifted basins around the Atlantic record a phase of intensive global compressional tectonics, associated with an important late Neogene plate reorganization of possibly global nature. These findings are also interesting in view of the partly overlapping occurrence of glaciation in Quaternary times. The onset of the observed acceleration in basin subsidence occurs well before the first occurrence of glaciation (1.6–1.9 Ma). This observation and the differential character of the uplift and subsidence at different positions within the rifted basins around the northern Atlantic rules out glaciation as the main cause for the late Neogene subsidence phases. On the other hand, it is well known that periods of increased elevations promote the development of glaciation (e.g. Powell & Veevers 1987). Although uplift in its own is only part of the dynamics of glaciation and changes in the air circulation patterns (Ruddiman & Raymo 1988), the intimacy of glaciations and uplift seems to be more than casual. An interesting consequence of stress-induced downbending in the central North Sea is an uplift of Norway and the British Isles. An intriguing observation is the occurrence of compressional Pliocene deformation along the Norwegian continental margin prior to the Quaternary uplift of Scandinavia (O. Eldholm, pers. comm. 1988). These findings suggest a causal link (Fig. 8) between the accumulation of compression during late Neogene time, inferred from the modelling of subsidence and stratigraphy of rifted basins around the northern Atlantic, and the onset of glaciation during Quaternary time. Thus the interesting perspective arises that uplift-induced glaciation by Himalayan and Rocky Mountain plateau uplift is augmented by uplift-induced glaciation along the northern Atlantic itself.

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