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5 Apparent sea-level fluctuations and a palaeostress field for the North Sea region

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A palaeostress curve derived from the sea-level record of the North Sea Basin mirrors the tectonic evolution of this region. Sea-level changes in the basins of north-western Europe can be associated with the major rifting and compressional episodes of Mesozoic and Tertiary ages. The major Tertiary lowerings in relative sea level at the basin margins can be interpreted in terms of increasing horizontal compression and the major falls in sea level coincide with the compressive folding phases of the Alpine orogeny.

The gradual rise in sea level recorded in the north-west European basins throughout the Jurassic and Cretaceous can be associated with the extensional tectonics and the periods of offlap can be associated with relaxation of the regional stresses as would result locally when active rifting occurs. Most of the Jurassic and Cretaceous North Sea offlaps do coincide with active rifting phases.

INTRODUCTION

During the last decade, major advances in quantitative analysis of the sea-level record in sedimentary basins have resulted from studies by Vail and his co-workers at Exxon (Haq *et al.*, 1987; Vail and Todd, 1981; Vail *et al.*, 1977; Vail *et al.*, 1984). Although the Vail *et al.* (1977) coastal onlap/offlap curves are based on data from various basins around the world, they have been heavily weighted in favour of North America, the Gulf Coast, the northern and central Atlantic margins and especially the North Sea. Their results, therefore, do not seem to be a true reflection of global changes; this is evident from Vail *et al.*'s (1977) Fig. 5, which shows several regions that conform with the 'global' pattern neither in magnitude nor in the timing of the cycles (see also Miall, 1986). At the same time there has been a continuous debate on the mechanisms that cause Vail *et al.*'s third-order cycles in sea level (e.g. Bally, 1980, 1982). Recently, Cloetingh *et al.* (1985) proposed a new tectonic mechanism for regional short-term sea-level variations (time scales of a few million years and longer) at rates of about 1–10 cm/1000 years with a magnitude of up to about hundred metres. Their model explains these changes, provided that horizontal stresses of the order of a few hundred MPa exist in the lithosphere and changes in these stress fields occur on geologic time scales. The proposed model (see Fig. 1(a)) represents the interaction between these stresses and the deflections of the lithosphere caused by sedimentary loading and thermal contraction (Sleep, 1971). Apparent sea-level changes of a rate and magnitude inferred from seismic stratigraphy can be produced at the flanks of sedimentary basins by this interaction (Fig. 1(b)). Therefore Cloetingh *et al.* (1985) pointed out that glacial fluctuations (Pitman and Golovchenko, 1983) are not the only mechanism capable of producing apparent sea-level fluctuations in excess of 1 cm/1000 years as well as magnitudes of about 100 metres. Alternatively, if the proposed mechanism is accepted then the apparent sea-level curves can be interpreted in terms of palaeostress fields (Cloetingh, 1986).

Several independent studies of lithospheric deformation in active continental margin and intraplate tectonic settings lead to the conclusion that horizontal stresses exist in the lithosphere and that these

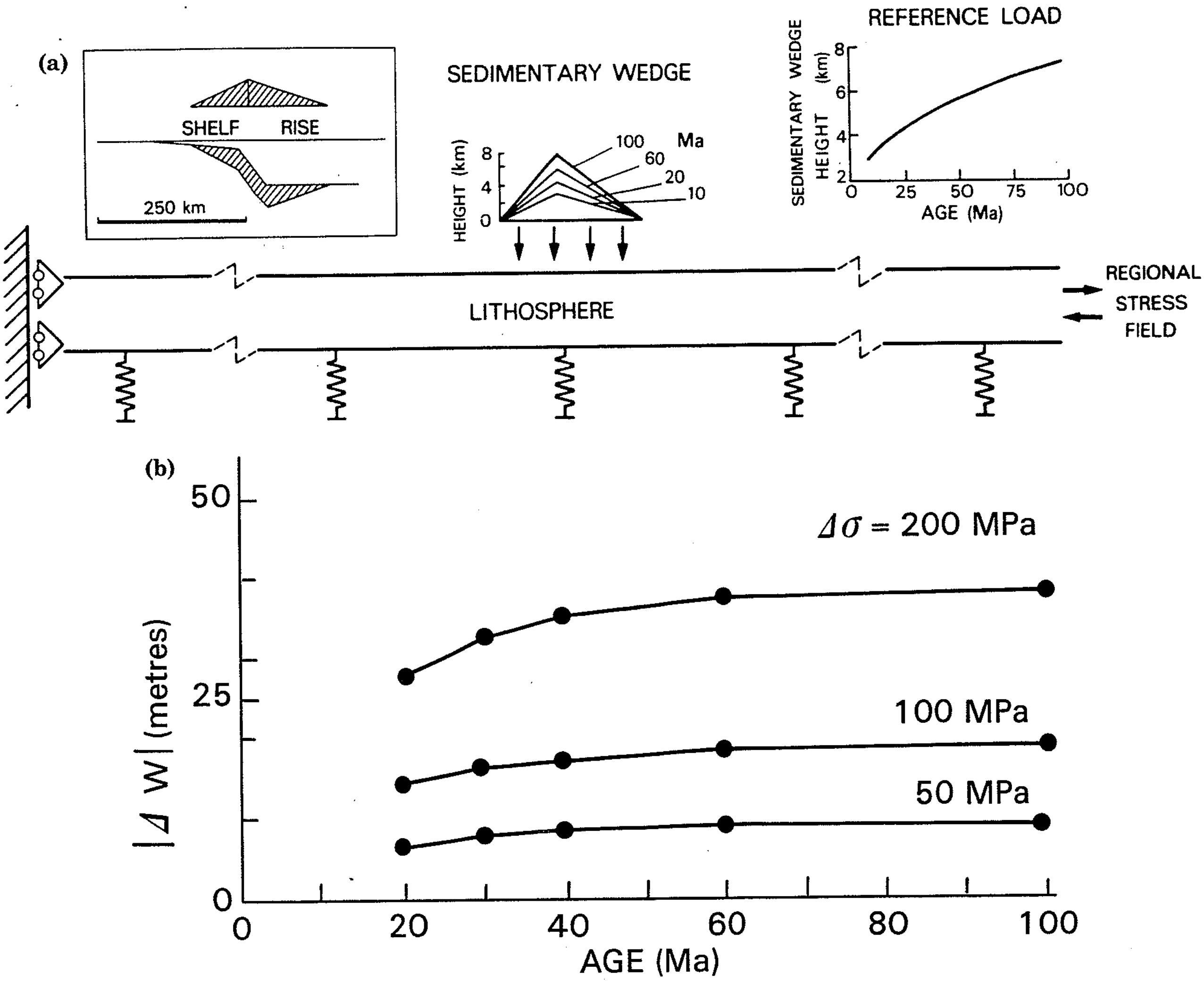

Fig. 1. (a) Model for apparent sea-level fluctuations resulting from variations in the in-plane stress field proposed by Cloetingh *et al.* (1985). The vertical displacement of the lithosphere at a passive margin evolves through time because of the thermal contraction and strengthening of the layer, and the sediment loading. The latter is represented by a wedge of sediments that grows with time (see inset on left for the position of this wedge on the outer shelf, slope and rise). The lithosphere is modelled mathematically as a uniform elastic layer overlying a fluid asthenosphere. Differences between continental and oceanic lithosphere are neglected. (b) Apparent sea-level fluctuation $|\Delta W|$ (metres) at basin edge (position marked by arrow in Fig. 2(a)) due to superposition of variations of regional stress field on flexure caused by sediment loading. The $|\Delta W|$ are plotted as a function of the age of the underlying lithosphere and sediment loading according to the reference model (after Turcotte and Ahern, 1977) of Fig. 1(a). Curves give results for stress changes of 50, 100 and 200 MPa, respectively.

stresses may reach magnitudes up to a few hundred MPa (Lambeck *et al.*, 1984; McAdoo and Sandwell, 1985; McQueen, 1986; Stephenson and Lambeck, 1985). Of interest here is the modification of the basin shape by variations in intraplate stress fields. Figure 2 schematically illustrates the relative movement between sea level and the crust at the edge of a basin immediately landward of the principal sediment load. When horizontal compression occurs, the peripheral flexural bulge is magnified and migrates in a seaward direction, uplift of the basement occurs, an offlap develops, and an apparent fall in sea level results, possibly exposing the sediments to produce an erosional or weathering horizon. For a horizontal tensional stress field, the flanks of the basin subside and migrate landwards, producing an apparent rise in sea level so that renewed deposition, with a corresponding facies change, is possible. The nature of this facies change depends, *inter alia*, on the nature of the sediment supply. Induced deflections in the centre of the basin, although of the same magnitude, are small compared to the total subsidence there and are of less stratigraphic significance. As the sign and magnitude of the apparent sea-level change will be a function of the location of the sampling point, however, this may provide a means of testing the tectonic model and, independently, of distinguishing this mechanism for eustatic contributions. In fact, Hallam (1987) has shown that a significant number of Jurassic unconformities are confined to the flanks of North Sea basins, consistent with the predictions of the tectonic mechanism. Our modelling has demonstrated (Cloetingh, 1987) that the incorporation of intraplate stresses in models of basin evolution can, in principle, predict a succession of onlap and offlap patterns such as observed along the flanks of the United States passive margin.

In this chapter (for a more detailed account see Lambeck *et al.*, 1987) we apply the tectonic model for apparent sea-level fluctuations proposed by Cloetingh *et al.* (1985) to the sea-level record published for north-western Europe. We have selected this region because, in the words of Ziegler (1978), this region is the crossroads of orogenic belts and rifts, where orogenic events have alternated with periods of rifting throughout Phanerozoic time. In consequence, the basin stratigraphy and apparent sea-level curves can be expected to exhibit considerable variations associated with changes in the stress regime.

THE APPARENT SEA-LEVEL RECORD OF NORTH-WESTERN EUROPEAN BASINS

Figure 3 summarizes some of the sea-level indicators that have been published for this region. The Tertiary result is from Vail *et al.* (1977) and appears to correspond to the Moray Firth Basin (Fig. 4 of Vail *et al.* 1977, Part 4). In this curve, gradual rises are followed by abrupt, nearly instantaneous falls, the largest of which, the Mid-Oligocene, is purported to have an amplitude of nearly 400 metres. Vail *et al.* (1984) and Haq *et al.* (1987) have interpreted these onlap–offlap sequences in terms of more gradual drops in sea level, and Fig. 3 also illustrates our modification of this curve following the modifications made by Vail and Hardenbol (1979) of their global Tertiary curve. There does not appear to be much support for the very large global sea-level change. Thorne and Bell (1983) derived a eustatic sea-level curve from histograms of North Sea subsidence which is consistent with lower estimates of the amplitude of the sea-level changes. Modelling subsidence at the United States passive margin (Watts and Thorne, 1984) also has provided revised quantitative estimates of the magnitude of the Mid-Oligocene fall in sea level, which is now estimated to be at most 50–60 metres. If this change is of tectonic origin then there is no reason why it should be everywhere of the same amplitude. Whether this particular change is of glacial origin remains questionable. Climatological indicators do suggest that temperatures were sufficiently low for the onset of glaciation to occur at this time but that major ice-caps did not form (Kennett, 1977); but even if the sea-level change is of glacial origin, some regional difference in magnitude can be expected (Nakada and Lambeck, 1987).

The Jurassic and Early Cretaceous onlap–offlap sequences have been published by Vail and Todd (1981); see also Vail *et al.* (1984) for two areas—the Inner Moray Firth and the Northern Viking Graben (Fig. 3). An independent result, based mainly on facies analysis, has been published by Hallam (1978, 1981). This is actually a 'global' curve but the results are very much dominated by north-western Europe and the eastern margin of North America prior to the Atlantic rifting (Figs 5–9 of Hallam, 1978), and all the variations seen in this curve are also seen in the North Sea data. As such, we adopt this result for comparative purposes. The Hallam and Vail *et al.* results are in good agreement (see also Hallam, 1984, 1987) although some differences in detail occur. Hallam, for instance, finds no evidence for the drop in sea level in the Early Jurassic (at the end of the Hettangian) and concludes that the Early Sinemurian is a time of sea-level rise, not fall (Fig. 3). The exceptionally high frequency of the occurrence of short-term fluctuations towards the end of the Jurassic occurs simultaneously with a pronounced increase in fault-controlled tectonic activity (Hallam, 1987). Hallam (1987) recognized a number of significant regressive events that appear to be caused by regional tectonics rather than 'global' fall in sea level.

Vail and colleagues have not published Mid and Late Cretaceous sea-level fluctuations for north-western Europe. Instead, we adopt the results based on facies analyses from the studies of Kauffman (1977) and Hancock and Kauffman (1978); see also Hancock (1984). Juignet (1980) has published two similar curves for the western part of the Paris Basin. He identified seven transgressive phases for this period, six of which can also be seen in the Kauffman and Hancock results (Fig. 3). The two drops in sea level in the Early Cretaceous, in the Late Aptian and Late Albian, can also be seen in the Vail and Todd (1981) global sea-level curve. Hallam suggests that the Jurassic rise in sea level was nearly 200 m while Juignet (1980) suggests a Cretaceous rise in sea level of about the same amount. As previously noted, it is important to recognize that if tectonic factors are responsible for this change, considerable regional variation in amplitude can occur because the horizontal stress propagation through the lithosphere need not be uniform and the initial perturbations will be variable.

A composite sea-level curve from Early Jurassic to the Late Miocene is illustrated in Fig. 3, and this should be viewed as indicative only of qualitative changes in sea level. The magnitude of the sea-level changes is scaled such that the Oligocene fall in sea level is 50 m. The principal first-order feature of this apparent sea-level curve is the gradual rise in sea level throughout Jurassic and Cretaceous time, followed by a fall in sea level during the Tertiary. This cycle is usually said to be of global extent even although it may also be appropriate to associate it with the break-up of Pangea along the Atlantic Ridge. These changes have been attributed to an increase in ocean-ridge volume during the Jurassic and Tertiary (Hallam, 1963; Pitman, 1978) although Pitman's model is associated with very considerable uncertainty (Kerr, 1984; Kominz, 1984). In this context, it is interesting to note that high-frequency oscillations in Cretaceous sea levels with characteristic periods of a few million years that cannot be correlated with fluctuations in spreading rates and ridge lengths (Schlanger, 1986), could be the result of adjustment of stresses in the process of the opening of the Atlantic. Modelling studies (Cloetingh and Wortel, 1986; Wortel and Cloetingh, 1983) suggest that rapid temporal fluctuations in intraplate stress fields occur, and geological evidence also points to episodic tectonic events on time scales of a few million years (Letouzey, 1986; Megard *et al.*, 1984). It is important to realize that the degree of correlation between the timing of sea-level changes induced by fluctuations in intraplate stress fields will depend primarily on the dimensions of the stress province. Numerical modelling (Cloetingh and Wortel, 1986; Wortel and Cloetingh, 1983) and observation of lithospheric deformation (Illies *et al.*, 1981; McAdoo and Sandwell, 1985; Zoback and Zoback, 1980) show that the stress provinces can vary in size from that of an entire lithospheric plate to that of a small part of a plate. The regional character of the tectonic mechanism proposed by Cloetingh *et al.* (1985) sheds new light on some observed deviations from the Vail *et al.* (1977) curve in areas in both the Northern (Harris *et al.*, 1984) and Southern (Carter, 1985; Chaproniere, 1984)

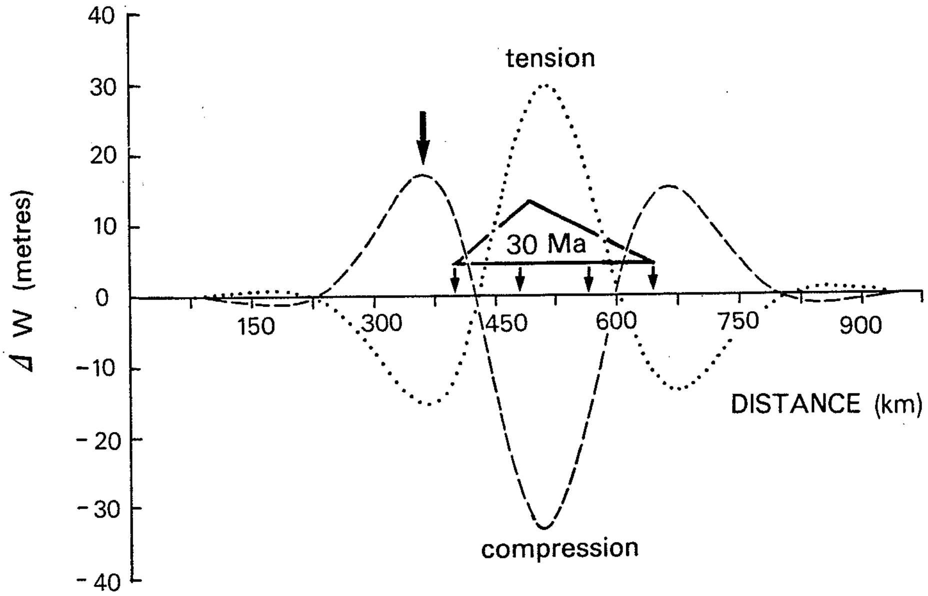

Fig. 2. (a) Effect of variations in intraplate stress fields on the deflection of a plate with a thickness corresponding to a lithospheric age of 30 Ma. Differential subsidence or uplift (metres) from the deflection in the absence of an intraplate stress field is given for intraplate stress fields of 100 MPa compression (dashed curve) and 100 MPa tension (dotted curve). (b) Idealized stratigraphy at the edge of a basin underlain by δ5 Ma-old lithosphere predicted on the basis of the calculations shown in Fig. 2(a).

hemispheres. While such deviations from a global pattern are a natural consequence of the character of the tectonic mechanism, they do not preclude the presence of global events in the stratigraphic record. These are to be expected when major reorganizations in lithospheric stress fields occur simultaneously in more than one plate, as conjectured for the early Cenozoic global plate reorganization (Rona and Richardson, 1978), or when glacial eustatic changes dominate.

A PALAEOSTRESS CURVE FOR NORTH-WESTERN EUROPE

If Cloetingh *et al.*'s (1985) model is assumed to be valid for the basins of north-western Europe, then it becomes possible to interpret the relative sea-level curve of the previous section in terms of changes in the regional stress state. There are several complications that call for caution in interpreting any results of such an inversion. First, in order to obtain quantitative estimates of stress, the mechanism of basin formation must be known as must the relevant lithospheric parameters. Different subsidence mechanisms may have operated within a given area at different times, and it would be important to examine relative onlap–offlap sequences from individual basins in the region and even from different locations within the same basin, rather than examine the regional curves. In particular, much of the subsidence may be fault controlled. Secondly, the relative sea-level change is likely to be a function of both tectonic and eustatic processes (Hallam, 1987). If both contribute within the same time interval then the interpretation of the sea-level curve becomes considerably more complex and not all of the fluctuations correspond to stress changes.

The tectonics of north-western Europe have been described in detail by Ziegler (1982). During the Mesozoic, the tectonics can be characterized as a predominantly horizontal tensional and stretching regime with the development of numerous grabens, until a few major grabens developed upon which much of the subsequent deformation was focused. The predominant mechanism of basin formation is therefore one of crustal stretching and subsidence (e.g. Barton and Wood, 1984; Sclater and Christie, 1980). During the Tertiary, the region was tectonically one of quiescence in which basin evolution was controlled mainly by thermal subsidence following upon lithospheric cooling. The region, however, was also affected by the compressional events of the Alpine Orogeny, producing some inversion of basins up to 1000 km north of the Alpine collision front (Ziegler, 1982). Ziegler (1982) and Sclater and Christie (1980) have pointed out the existence of a correlation between tectonic phases in the North Sea Basin and changes in the history of opening of the Atlantic and Tethyan oceans (see also Schwan, 1985, for a more general discussion). Changes in spreading rates in the Atlantic and Tethyan regions are probably caused by, or associated with, changes in plate-tectonic forces. Both modelling of lithospheric stress fields (Cloetingh and Wortel, 1985; Richardson *et al.*, 1979; Wortel and Cloetingh, 1983) and measurement of directions of present-day stress fields (Illies *et al.*, 1981; Klein and Barr, 1986) and palaeostress fields (Letouzey, 1986; Letouzey and Tremolieres, 1980) demonstrate that the induced stress changes are propagated over great distances from the plate boundaries into the north-western European basins, which provides a dynamic explanation for the observed correlations. Tectonic lineation rosettes,

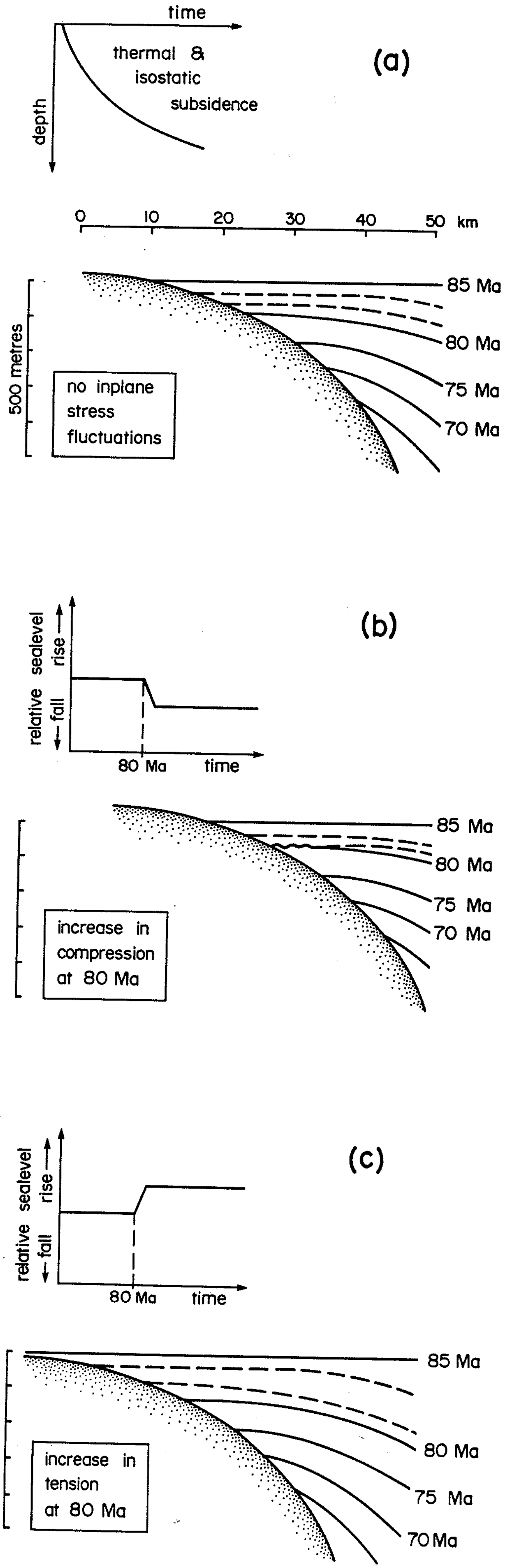

Fig. 2b. (a)—Onlap associated with cooling of the lithosphere in the absence of an intraplate stress field. The subsidence curve is illustrated on the left. (b)—A transition (in an interval ΔT) to 50 MPa compression at δ0 Ma induces a short-time phase of offlap at that time and an apparent fall in sea level superimposed on the thermal cooling subsidence curve. (c)—A transition to 50 MPa tension produces an additional short-term phase of onlap at δ0 Ma; that is, the subsidence will appear to be greater than predicted by the thermal-cooling subsidence model, and this may lead to a facies change in the sedimentation. The figures on the left represent the incremental change in the onlap and in apparent sea level.

determined from spectral analysis of North Sea tectonic subsidence, show a rotation from a prominent E–W trend in the Triassic to N–S in the Late Cretaceous (Thorne, 1986), a trend also reflected in the measured paleostress orientations (Letouzey, 1986). The influence of the Alpine Orogeny is reflected in differences in orientation between Pliocene and other Cenozoic directions (Thorne, 1986). As noted by Letouzey (1986), Late Cretaceous to present compressive pulses along the Alpine belt and in foreland regions are related to plate convergence and collision. Furthermore, a causal relationship might exist between these stress changes and the timing of salt diapirism in the North Sea Basin (Thorne, 1986).

The specific model of Cloetingh *et al.* (1985) is not appropriate for this region during the Mesozoic. Nevertheless, the concept of a mechanism of steady subsidence modulated by changes in the magnitude of the horizontal regional tensional force can be applied for this time interval. Without specifically developing such a model it is not possible to quantify the stress field. The first-order cycle of Mesozoic sea-level rise and Tertiary fall is consistent with a horizontal stress regime that is predominantly one of tension during the Mesozoic (Fig. 4), resulting in subsidence of the basin floor either by graben formation and subsidence of the graben flanks by sediment loading (Beaumont, 1978), or through crustal stretching (McKenzie, 1978). The latter mechanism requires tensional stresses of the order of a few hundred MPa (Cloetingh and Nieuwland, 1984; Houseman and England, 1986).

By the Late Cretaceous, a reduction in tension, or even a change to overall compression, produced a reversal of this trend. Superimposed upon these long-term cycles were numerous rises and falls in apparent sea level, many of which can be associated with specific tectonic phases within north-western Europe (Ziegler, 1982). The Early Jurassic to Early Tertiary Laramide tectonic phases (Fig. 4), appear to have been predominantly tensional events that affected north-western Europe as a whole and which are also seen beyond this region. These events appear as renewed phases of rifting associated with the foundering of Pangea, and this part of the sea-level curve can be interpreted in terms of periods of gradual stretching and subsidence, followed by periods of lithospheric relaxation, or failure and rifting, when this stress is partially released and sea levels at the edges of the basins appear to fall. The cycle then repeats itself. Within this framework, periods of gradual increase in sea level are associated with times of more gradual build-up of tension and stretching, while the lowering of sea level is associated with discrete rifting episodes. Most of the

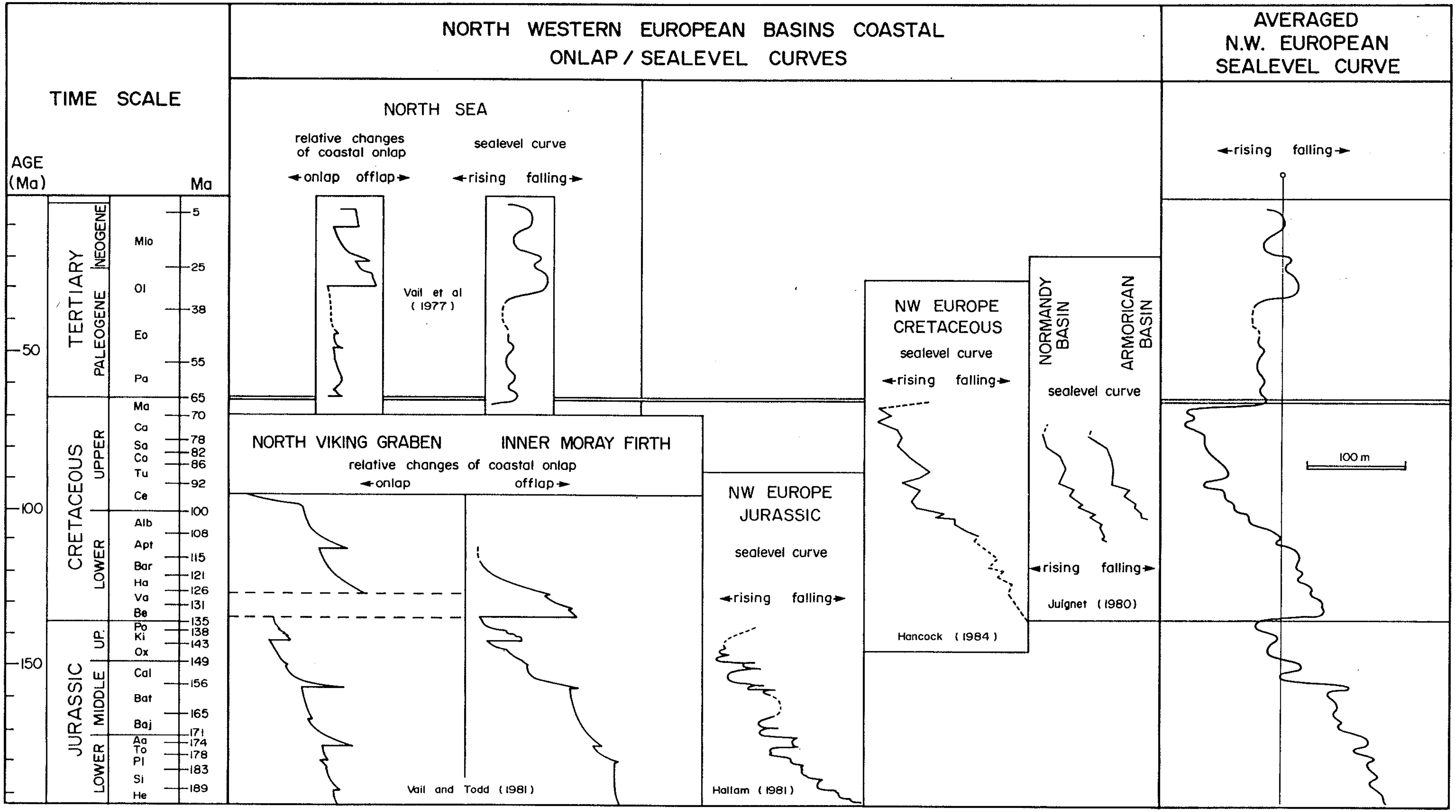

Fig. 3. Mesozoic–Cenozoic onlap/offlap curves and apparent sea-level variations. Columns from left to right give the Vail *et al.* (1977) Tertiary North Sea curve, its modification based on the Vail and Hardenbol (1979) revised 'global' curve, the Jurassic onlap/offlap curves given by Vail and Todd (1981) for the Northern Viking Graben and the Inner Moray Firth, the Jurassic sea-level curve by Hallam (1981), the Cretaceous North Sea curve from Hancock (1984) and the Cretaceous sea-level curves for the Paris Basin by Juignet (1980). The last column is an average Mesozoic–Cenozoic sea-level curve for the north-western European basins based on the information given in the columns to its left. To establish a scale for the sea-level change we adopt a magnitude of 50 m for the Oligocene lowering in sea level, a further 150 m rise in the Cretaceous and a 150 m rise in the Jurassic (after Lambeck *et al*, 1987).

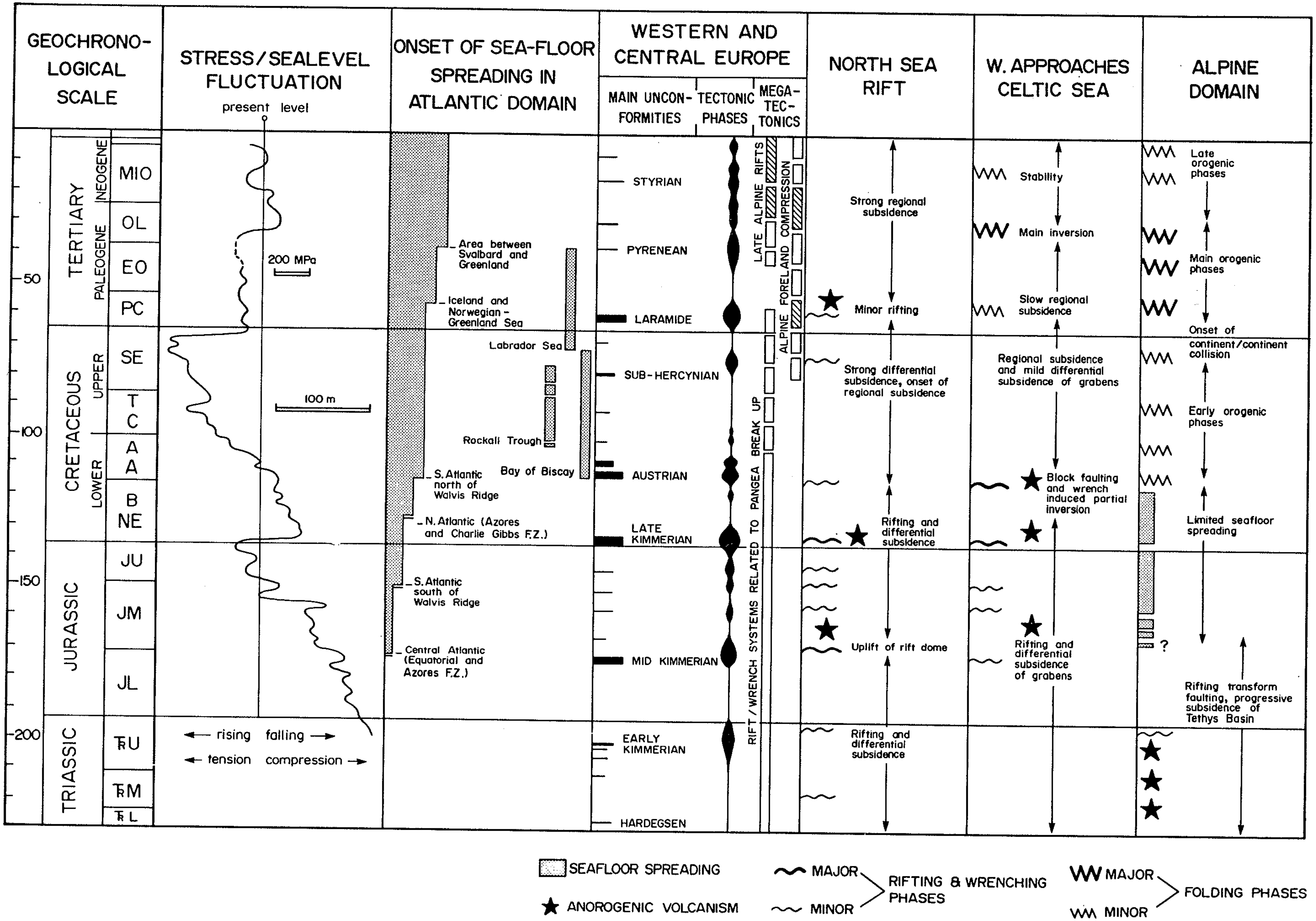

Fig. 4. Synthetic palaeostress curve derived from the generalized sea-level curve for the north-western European basins given in Fig. 3. Stresses are plotted relative to an arbitrary present-day stress level. Comparison with columns on the right-hand side with the timing of tectonic events in north-western Europe (after Ziegler, 1982) shows correlation with tectonic phases in the Atlantic, the North-western European rift system and the Alpine domain. Thick and thin wavy lines denote major and minor rifting phases, respectively. Major and minor folding phases are indicated by thick and thin saw-tooth lines; stars denote phases of anorogenic volcanism (after Lambeck *et al*, 1987).

Jurassic and Cretaceous North Sea rifting episodes do, in fact, correlate well with these apparent lowerings in sea level, as has already been noted by Ziegler (1978).

The sea-level falls in the Mid-Cretaceous (Cenomanian and Turonian) do not appear to correspond to North Sea rifting episodes, but they occur at a time of active development of the Rockall Trough and the opening of the Bay of Biscay (Ziegler, 1982). The Laramide tectonic phase is considered to be a mild rifting phase, and its association with a substantial drop in sea level would appear to be inappropriate here. The major Tertiary lowerings of sea level occur at times of the various folding phases of the Alpine Orogeny. In particular, the Mid-Oliogocene change in sea level corresponds to one of the main compressive phases of the orogeny, while the Mid-Palaeocene drop may be more appropriately associated with the first of the three main orogenic phases than with the mild rifting episode seen at about the same time in the North Sea. From Fig. 4, the change in stress required to produce the Mid-Oligocene drop in sea level of about 50 m is about 200–300 MPa. This is very much an upper limit; stress relaxation and a depth-dependent rheology, an effectively young crust, episodes of rapid sedimentation and movements on existing faults can all lead to substantially larger deflections of the lithosphere than is predicted by the elastic model upon which Fig. 1(b) is based. The majority of the other apparent sea-level changes require smaller variations in stress, and are well within the range of horizontal stress differences observed in the lithosphere.

Distinguishing regional events in the sea-level record from eustatic signals is usually a subtle matter, especially if biostratigraphic correlation is imprecise (Hallam, 1984, 1987). In this chapter, a palaeostress curve for the North Sea region has been derived from the sea-level record on the assumption that the apparent sea levels are controlled by regional tectonics. A further and more detailed examination of the stratigraphic record of individual basins in the North Sea area, in connection with independent numerical modelling of palaeostresses in north-western Europe using techniques developed by Wortel and Cloetingh (1981, 1983) and Cloetingh and Wortel (1985, 1986), provides an additional and new approach for separating eustatic and tectonic components in the sea-level record of this region.

CONCLUSIONS

The North Sea sea levels for the Jurassic to Tertiary exhibit numerous fluctuations on a time scale of a few million years and longer, superimposed upon long-term (time scales of the order of 100 Ma) fluctuations. The latter can be attributed to the change in the predominant horizontal stress state of the lithosphere from one of significant tension and crustal thinning to one of less tension or even compression. The short-period fluctuations can be interpreted as the irregular response of the crust in the form of rifting episodes, or of compressional pulses to the more regional stress state. Quantitative estimates for the changes in stress field required are of the order of about 200 MPa for Tertiary times but, as previously emphasized, these are upper limits.

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