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Intraplate stresses and the stratigraphic evolution of the North Sea Central Graben

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Abstract

We present results of stratigraphic modelling and quantitative analysis of subsidence data for the southern part of the North Sea Basin. Tectonic subsidence curves are given for fifteen wells in the northernmost segment of the Dutch North Sea and the southern part of the Dutch Central Graben. These curves have been supplemented with tectonic subsidence curves for eight wells from the Broad Fourteens and West Netherlands Basins. Subsidence analysis and thermo-mechanical modelling show that Late Jurassic and Early Cretaceous multiple stretching phases with a finite duration are required to explain the observed stratigraphic record. Our analysis demonstrates the important role of intraplate stresses in the evolution of these basins. The paleo-stress curve inferred from the stratigraphic modelling shows a trend with a change from tensional and neutral stresses during Mesozoic times to a stress regime of more overall compressional character during Cenozoic times. Superimposed on this long-term trend are short-term stress fluctuations. This paleo-stress curve and the associated stratigraphic record of the Dutch North Sea Basin sheds light on the record of paleo-stress measurements in the Northwestern European platform and is consistent with data on the kinematic evolution of the Tethys belt. These findings demonstrate the key-importance of tectonics and stress-induced vertical motions – related to rifting events in the northern Atlantic region and the interaction of the Eurasian and African plates – in controlling the stratigraphic evolution of the North Sea Basin.

Introduction

During the last few years considerable progress has been made in quantative modelling of sedimentary basin development (see for a review Beaumont & Tankard 1987). These studies have demonstrated the important role of thermo-mechanical properties of the lithosphere in models of basin evolution (e.g. Watts et al. 1982). Furthermore, they have quantified the contributions of a variety of geodynamic processes to the vertical motions of the lithosphere at sedimentary basins. These processes include thermal contraction induced by cooling of the lithosphere amplified by the loading of sediments that accumulate in these basins (Sleep 1971), isostatic response to crustal attenuation by stretching (McKenzie 1978), and flexural bending in response to vertical loading (Beaumont 1978). The increase in flexural rigidity associated with long-term cooling of the lithosphere upon rifting has been shown to explain adequately the long-term widening of rifted basins and the associated long-term (on time scales of several tens of Ma) sea level record (Watts 1982).

A new key element in basin modelling is the incorporation of intraplate stresses in stratigraphic modelling (Cloetingh 1988). Cloetingh et al. (1985) and Cloetingh (1986) have demonstrated that fluctuations in intraplate stress fields provide a tectonic explanation for short-term (1–5 Ma) fluctuations in apparent sea level. These fluctuations in intraplate stress fields are superimposed on the tectonic subsidence induced by the driving mechanisms mentioned above (see Fig. 1). Vertical motions of the lithosphere at basin flanks (or apparent sea level changes) are induced at a rate and magnitude consistent with analysis of the seismic stratigraphic record (Vail et al. 1977, Haq et al. 1987). Figure 2 schematically illustrates the effects of changes in intraplate stress on the stratigraphy at the edge of a sedimentary basin calculated for an elastic lithosphere. When horizontal compression occurs, the peripheral bulge flanking the basin is magnified, resulting in uplift of the basin flanks and seaward migration of the shore line. An offlap develops and an apparent fall in sea level results, possibly exposing the sediments, thus causing the development of an unconformity. Simultaneously, the basin centre deepens, resulting in a steeper basin slope. For a horizontal tensional intraplate stress field, the flanks of the basin subside. This results in a landward migration of the shore line and an apparent rise in sea level so that renewed deposition with a corresponding facies change is possible. In this case the centre of the basin shoals, and the basin slope is reduced. The synthetic stratigraphy at the basin edge is schematically shown for the following three situations: long-term widening of the basin with cooling in the absence of an intraplate stress field (Fig. 2a); the same case with a superimposed transition to 500 bar compression (Fig. 2b); and the case of a stress change to 500 bar tension (Fig. 2c).

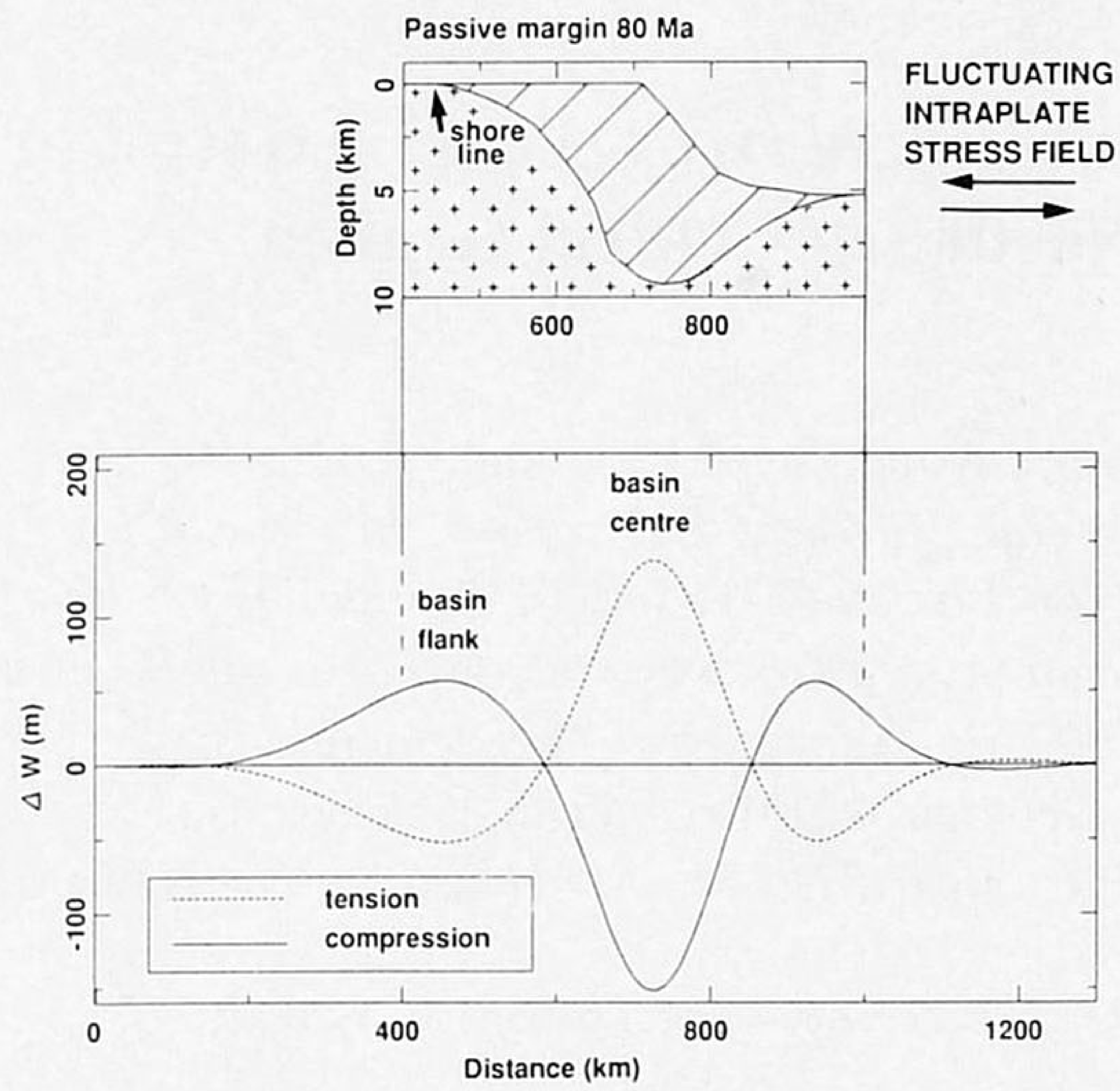


Fig. 1. Flexural deflections at a sedimentary basin induced by changes in the intraplate stress field. Sign convention: uplift is positive, subsidence is negative. Above: an 80 Ma old passive margin initiated by stretching. The wedge of sediments flexurally loads an elastic plate. The thickness of this 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 margin is uplifted and the basin centre subsides. A change to 1 kbar tension (dashed curve) induces uplift of the basin centre and subsidence of 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).

These short-term cycles in apparent sea level have been traditionally interpreted in terms of a glacioeustatic control. However, with the exception of the Oligocene events, there is no evidence in the geological and geochemical records for significant Mesozoic and Cenozoic glacial events prior to Middle Miocene times (Frakes 1979). Glacio-eustatics, therefore, cannot explain those major parts of the apparent sea level record where glacial phases are thought to have been insignificant (Pitman & Golovchenko 1983). Furthermore, changes in intraplate stress fields associated with tectonic reorganizations in the lithosphere also explain the existence of a strong correlation (Bally 1982) between the timing of plate reorganizations and rapid low-

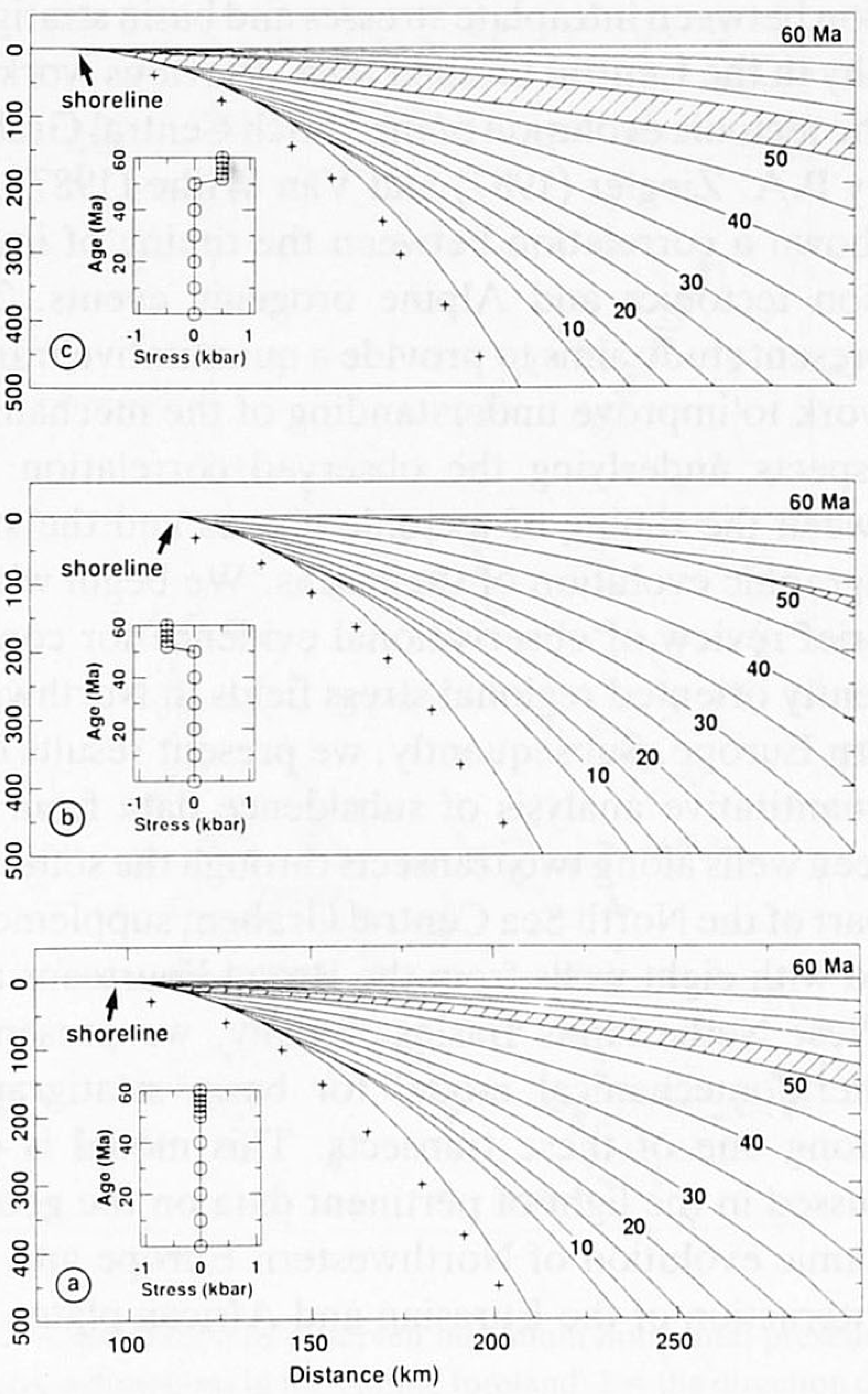


Fig. 2. Synthetic margin stratigraphy for a 60 Ma old basin, which is initiated by lithospheric stretching followed by thermal subsidence and flexural infilling of the resulting isostatic depression. Shading indicates the position of a sedimentary package bounded by isochrons of 50 Ma and 52 Ma after basin formation. a) Stratigraphy with zero-intraplate stresses. b) Effect of a stress change to 500 bar compression at 50 Ma. Stress-induced uplift of the peripheral bulge induces narrowing of the basin and a phase of rapid offlap, followed by a long-term phase of gradual onlap due to thermal subsidence. c) Effect of a stress change to 500 bar tension at 50 Ma. Stress-induced downwarping of the peripheral bulge causes widening of the basin and a phase of rapid basement onlap.

erings in sea level shown in the Vail et al. (1977) curves.

Simultaneously, considerable progress has been made recently in the study of the lithospheric stress field itself. Detailed analysis of earthquake focal mechanisms, in-situ stress measurements and analysis of break-out orientation logs taken in wells drilled for commercial purposes have demonstrated the existence of consistently oriented stress provinces in the lithosphere (Zoback 1985, Klein & Barr 1986). At the same time, numerical modelling (Wortel & Cloetingh 1981, 1983; Cloetingh & Wortel 1985, 1986) has yielded better understanding of the causes of the observed variations in stress level and stress directions in the various lithospheric plates. These studies have demonstrated a causal relationship between processes at plate boundaries and deformation in the plate's interiors (e.g. Johnson & Bally 1986). Similarly, substantial progress has been made in quantifying the stress levels associated with compressional and extensional deformation. Folding of oceanic lithosphere in the Bay of Bengal, for example, has been shown to require compressional stress levels of the order of several kbars (McAdoo & Sandwell 1985), a stress level that is in excellent agreement with independent estimates of the stress level in the northeastern Indian Ocean (Cloetingh & Wortel 1985). The formation of sedimentary basins by lithospheric stretching requires tensional stress levels also on the level of a few kbars (Cloetingh & Nieuwland 1984, Houseman & England 1986).

Given current active research in sea level fluctuations, the possibility that the effect of intraplate stresses is significant has been explored for various regions. Schlanger (1986) suggested that intraplate stress variations provide a possible explanation for the enigmatic high frequency (order of a few Ma) variations in Cretaceous apparent sea levels. Hallam (in press) discussed the implications of such variations for the Jurassic sea levels of northwestern Europe. Meulenkamp & Hilgen (1986) explored a causal relation between Neogene stratigraphy in the eastern Mediterranean and intraplate stress variations. De Vries-Klein (1987) examined the stratigraphic record of the Paleozoic Appalachian foreland basin and concluded that local variation and local tectonic styles and associated changes in stress field might have masked the possible expressions of global fluctuations in sea levels.

Recently, we have concentrated on the North Sea area to explore the potential use of the sea level record as a new source of information on paleostresses (Cloetingh 1986, Lambeck et al. 1987, Cloetingh et al. 1987). This choice was primarily motivated by the documented occurrence of important temporal changes in tectonic regime, a feature that is inherent to the location of the North Sea area relative to the North Atlantic rift system and the Alpine fold belt (P.A. Ziegler 1982). Furthermore, the North Sea area has played a crucial role in the construction of the Exxon 'global' sea level charts (see Vail et al. 1977, their figure 5). However, the traditional interpretation of the sea level record in terms of glacio-eustatics has been the subject of increasingly intensive debate. As has been realized by several authors (Parkinson & Summerhayes 1985, Miall 1986, Summerhayes 1986, Hallam, in press) several features displayed in the Vail third-order cycles may actually reflect North Sea Basin tectonics. Therefore, the North Sea area is of key importance to examine the relative contributions of glacio-eustatics and tectonics to the observed sea level fluctuations.

The tectonic history of the North Sea area can be divided into several stages (P.A. Ziegler 1975, 1978, 1982; W.H. Ziegler 1975). The North Sea Permo-Triassic basin was formed after the Variscan geosynclinal stage. Sedimentation took place in the Northern and Southern Permian Basin separated by the Ringkobing-Fyn and Mid North Sea High. Rifting occurred during Early Triassic to Early Cretaceous, abated subsequently and ceased altogether during the Late Paleocene. Rifting prevailed contemporaneously with the opening of the Atlantic, with the strongest rifting pulses occurring during Late Jurassic and Early Cretaceous. During Late Cretaceous and early Tertiary fault block-movement – and associated differential subsidence – were reactivated in response to the Laramide compressional phases, resulting in some very prominent basin inversions. Subsequently, a wide Cenozoic basin developed which is nearly unaffected by faulting. As demonstrated by P.A. Ziegler (1982) there is a correlation between the timing of most of the short-term lowerings in sea level and the major rifting and compressional episodes of Mesozoic and Tertiary ages.

In the present paper we discuss results of a quantitative analysis of subsidence data and modelling of basin stratigraphy for the southern part of the North Sea Basin. In doing so we focus on the relation between intraplate stresses and basin stratigraphy in the Central Graben area. Previous work on the tectonic evolution of the Dutch Central Graben by P.A. Ziegler (1987) and Van Wijhe (1987) has shown a correlation between the timing of inversion tectonics and Alpine orogenic events. The present study aims to provide a quantitative framework to improve understanding of the mechanical aspects underlying the observed correlation between the timing of tectonic phases and the stratigraphic evolution of the basins. We begin with a brief review of observational evidence for consistently oriented regional stress fields in Northwestern Europe. Subsequently, we present results of a quantitative analysis of subsidence data from fifteen wells along two transects through the southern part of the North Sea Central Graben, supplemented with eight wells from the Broad Fourteens and West Netherlands Basins. Finally, we present a thermomechanical model for basin stratigraphy along one of these transects. This model is discussed in the light of pertinent data on the geodynamic evolution of Northwestern Europe and the interaction of the Eurasian and African plates.

Regional stress field in Northwestern Europe

The existence of a present-day compressive regional stress field in the upper crust of the Alpine foreland of Northwestern Europe has been inferred from a wide range of observational techniques. The stress pattern as determined by in-situ stress techniques and analysis of break-out orientation logs from oil wells is largely consistent with stress directions inferred from analysis of focal mechanisms of earthquakes (Klein & Barr 1986). The general trend of the horizontal component of maximum compressive stress σ_1 is SE-NW (about 140°), a trend that is remarkably uniform over large distances. These features provide strong evidence for far-field stress propagation away from the Alpine collision from (Klein & Barr 1986, see Fig. 3). Local deviations from the overall stress pattern are observed mainly along zones of active strain release such as the Rhine Graben (Illies et al. 1981).

Paleo-stress patterns for the Alpine foreland

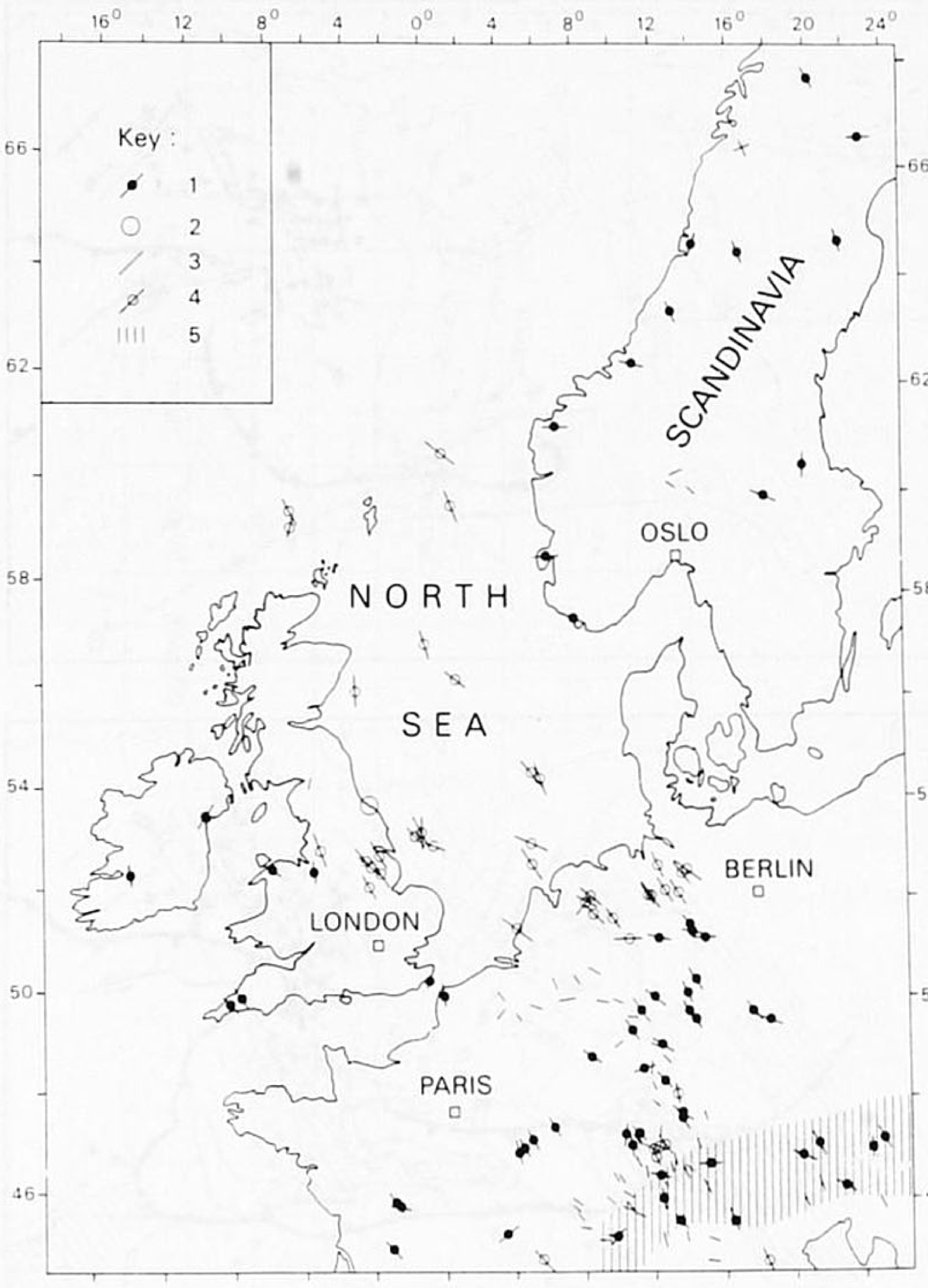


Fig. 3. Compilation of observed maximum horizontal present-day stress directions in the Alpine foreland. 1 = the direction of maximum horizontal stress from in-situ measurements, 2 = a horizontal stress equal in all directions found from in-situ measurements, 3 = the direction of maximum horizontal stress inferred from earthquake focal mechanism studies, 4 = the direction of maximum horizontal stress based on break-out analysis, 5 = Alpine fold belt. The data indicate stress propagation away from the Alpine fold belt in the platform region (after Klein & Barr 1986).

have been deduced from measurements on microstructures in sedimentary rocks such as stylolites, tensional joints and from movements on small faults (Letouzey 1986, Bergerat 1987). These authors demonstrated the relatively uniform character of the paleo-stress patterns in both time and space in the Cenozoic (Fig. 4). The regional stress field during Cenozoic times seems to be primarily controlled by European-African plate convergence and continental collision. Although the regional stress field is of overall compressive character, it has been subject to important temporal variations. Changes in magnitude (Letouzey 1986) and rotation of principal stress axes in adjustment to migration of the European-African rotation pole are observed (Bergerat 1987, Letouzey 1986). Inversion of parts of subsiding graben systems during the Late Cretaceous and early Tertiary and the timing of these events also provide strong evidence for transmission of compressive stresses from the Alpine collision front throughout the Alpine foreland over distances of the order of 1000 km (P.A. Ziegler 1987).

Subsidence analysis of well data

The sedimentary record provides key information on vertical motions of the lithosphere and, consequently, on the tectonic subsidence underlying the formation and evolution of a basin. As the tectonic subsidence of a basin is amplified by sediment loading, a correction for this effect has to be applied before the driving tectonic subsidence can be extracted from the stratigraphy. This procedure is commonly called backstripping (Steckler & Watts 1978) or geohistory analysis (Van Hinte 1978).

We have calculated (water loaded) tectonic subsidence through time using methods discussed by Seckler & Watts (1978), Sclater & Christie (1980) and Bond & Kominz (1984). In this study we have adopted the Harland et al. (1982) time scale. Lithological effects, in particular compaction and extreme densities of evaporites, have been corrected for. Each stratigraphic unit between two chronostratigraphic horizons has been assigned a sand, silt, shale, carbonate, anhydrite and halite percentage with each lithology responding according to its own compaction scheme. Minimum and maximum limits of lithological effects have been tested which showed that associated uncertainties in tectonic subsidence are of the order of up to several tens of metres. We have used the stratigraphic nomenclature of The Netherlands (NAM & RGD 1980) for the interpretation of the stratigraphy. Paleo-water depth data have been used for three wells together with information on long-term eustatic sea level changes. For the other wells we adopted an arbitrarily constant paleo-water depth of 100 metres. We have assumed Airy isostasy in the analysis of the subsidence data. By doing so we have ignored the

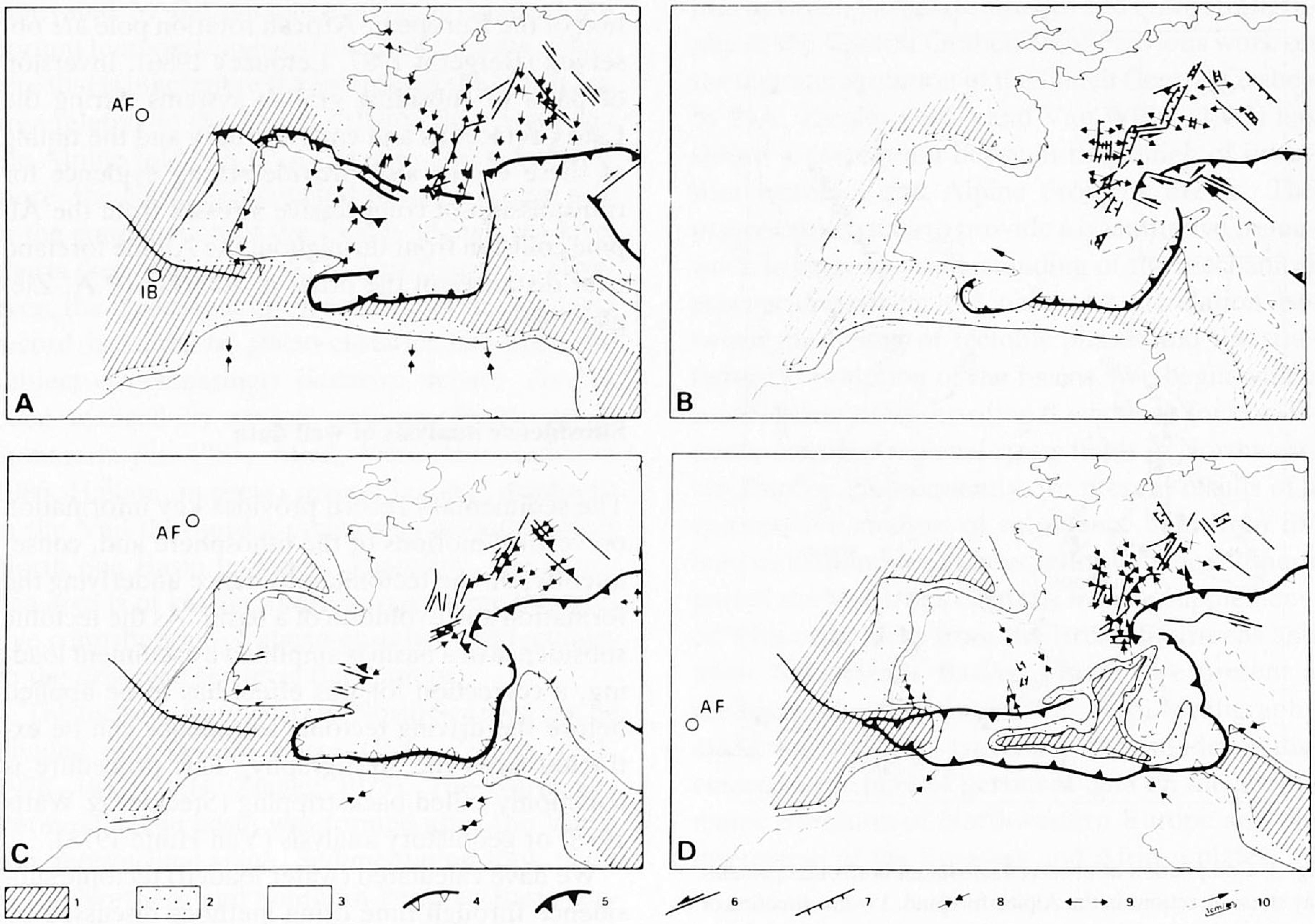


Fig. 4. Paleo-stress directions in the Alpine foreland. a) Late Eocene (40 Ma). b) Oligocene (35–30 Ma). c) Early Miocene (22–20 Ma). d) Late Miocene to post-Miocene (7–4 Ma). 1 = oceanic crust, 2 = thinned continental crust, 3 = continental crust, 4 = subduction zone, 5 = overthrust belt, 6 = strike-slip fault, 7 = normal fault, 8 = azimuth of the main maximum stress σ_1, 9 = azimuth of the main minimum stress σ_3, 10 = relative vector of motion Africa/Eurasia in centimetres/year (after Bergerat 1987).

effect of a finite strength of the lithosphere on its response to sediment loading. This assumption, however, does not significantly affect the shape of the inferred subsidence curves (Watts et al. 1982). This also implies that flexural effects of intraplate stresses have been retained in these curves. Similarly, we have ignored the reduced basement cooling due to the blanketing effect of sediments (Turcotte & Ahern 1977, Lucazeau & Le Douaran 1985). To incorporate this effect in the analysis would require detailed knowledge of the thermal structure of the lithosphere throughout the basin evolution. Furthermore, due to the long time scale on which lithospheric cooling operates (order of tens of Ma), a correction for the effect of blanketing (order of magnitude of up to 100 metres) will not significantly alter the slope of the tectonic subsidence curves (Lucazeau & Le Douaran 1985).

The locations of the wells used in the present analysis are given in Fig. 5 and Table 1. The wells have been selected for three regions; the northernmost part of the Dutch North Sea, the Dutch Central Graben area (54° N) and the Broad Fourteens/West Netherlands Basins, respectively. Because commercial bore holes are normally placed on prospective structures some deviations from the regional subsidence pattern can be expected. These features will be treated further on together with estimates of the magnitude of uplift phases, associated with an erosional expression in the stratigraphy, obtained from regional seismic lines.

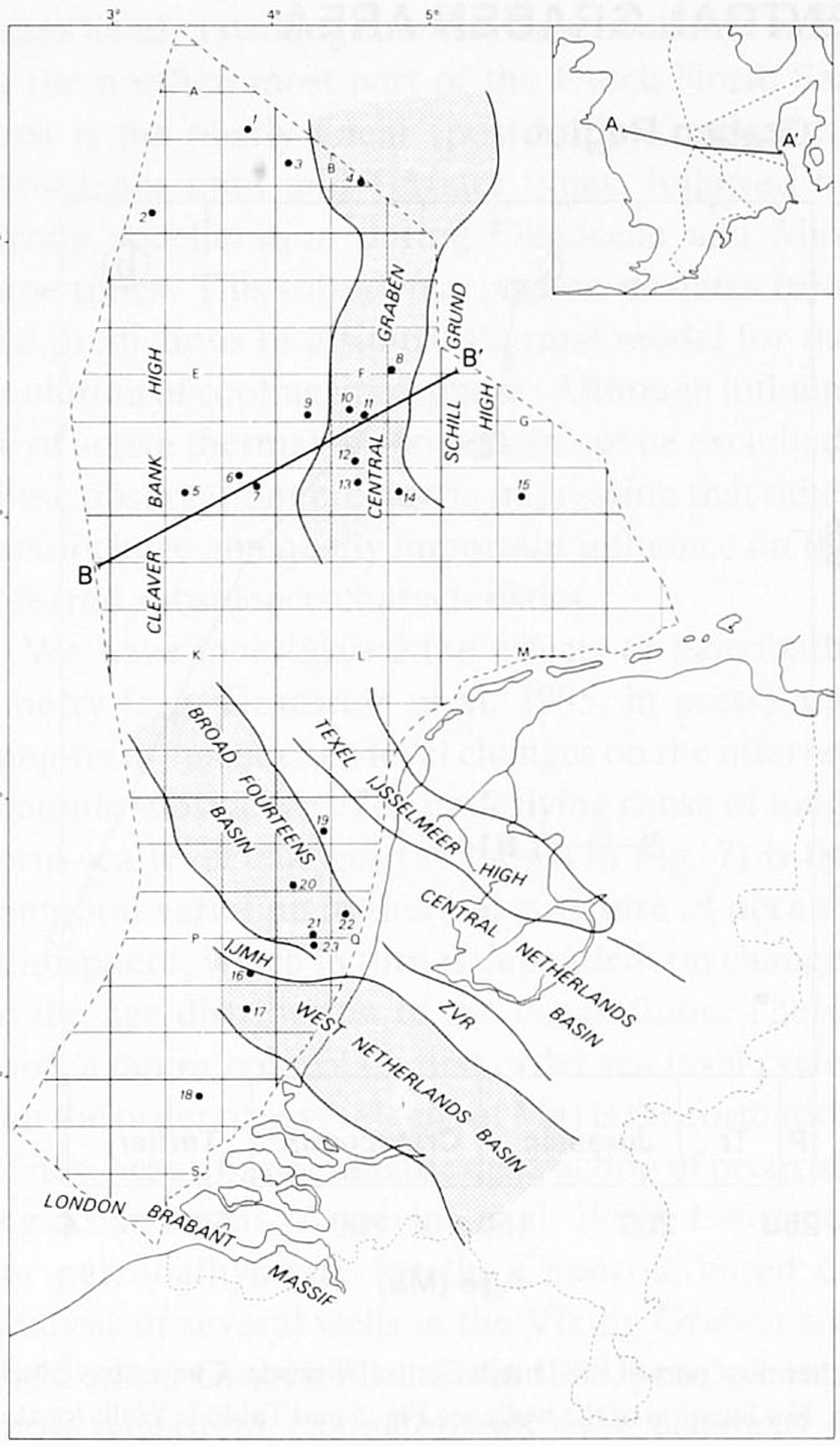


Fig. 5. Simplified tectonic map of the Dutch Central North Sea. Wells used in the present study are indicated by dots. Numbering of the wells refers to convention used in Table 1. Otherwise, wells are named after the blocks in which they are situated. The location of the stratigraphic cross-section AA' through the northernmost part of the Dutch Central Graben is shown in the inset. Line marked by BB' indicates the position of a NOPEC seismic line. ZVR and IJMH denote Zandvoort Ridge and IJmuiden High respectively.

Northernmost part of the Dutch North Sea

Tectonic subsidence curves for four wells in the northernmost part of the Dutch sector of the North Sea are displayed in Fig. 6. Horizontal dashed lines in the tectonic subsidence curves indicate a truncation in subsidence and correspond to stratigraphic unconformities. This representation is clearly a simplification as an erosional hiatus is usually associated with complex motions of the basement.

Evidence is lacking for net Middle Triassic to Late Jurassic subsidence in the area of the A-wells on the western flank of the Central Graben (Mid North Sea High). This is in agreement with observed deep truncation caused by Middle Jurassic upwarping of the Central North Sea rift dome and uplift of the rift flanks during the Late Triassic rifting phase. Evidence for subsidence in the latest Jurassic can be found in the Graben area (B14-1) at an earlier stage (Callovian) than in the flank region, which suggests that either renewed subsidence first occurred in the graben, or that Callovian sediments have been removed from the flanks during the Oxfordian. The latter possibility is associated with a short-term fall in relative sea level, which can be explained by relaxation of tensional stresses. This mechanism is strongly supported by the presence of a short-wavelength Oxfordian-Portlandian crustal bulge on both sides of the Central

Table 1. Summary of boreholes used in this study.

Nr.	Well	Latitude (°*N*)	Longitude (°*E*)	Penetration Depth (m)
1	A12-1	55° 24′ 00.1″	03° 48′ 33.9″	3404
2	A16-1	55° 07′ 28.1″	03° 15′ 11.9″	2678
3	B13-1	55° 18′ 01.2″	04° 04′ 30.2″	2837
4	B14-1	55° 12′ 16.9″	04° 34′ 35.5″	2525
5	E17-1	54° 05′ 38.8″	03° 25′ 26.2″	3727
6	E18-1	54° 07′ 40.9″	03° 53′ 10.3″	2463
7	E18-2	54° 09′ 05.0″	03° 46′ 38.2″	4445
8	F9-2	54° 30′ 56.8″	04° 43′ 32.5″	2382
9	F10-1	54° 21′ 57.4″	04° 13′ 59.1″	3433
10	F11-1	54° 22′ 04.0″	04° 35′ 39.0″	2920
11	F11-2	54° 24′ 54.6″	04° 27′ 38.8″	2663
12	F14-1	54° 11′ 39.5″	04° 30′ 32.0″	2977
13	F17-1	54° 08′ 43.6″	04° 31′ 41.9″	3871
14	F18-1	54° 05′ 54.0″	04° 44′ 32.0″	3718
15	G17-1	54° 04′ 29.9″	05° 30′ 41.0″	3955
16	P12-1	52° 23′ 18.9″	03° 52′ 38.4″	3554
17	P15-1	52° 15′ 36.8″	03° 51′ 32.8″	3224
18	S2-1	51° 57′ 10.1″	03° 33′ 28.7″	1766
19	Q1-2	52° 53′ 04.6″	04° 18′ 52.4″	3072
20	Q4-1	52° 41′ 14.6″	04° 07′ 20.1″	3105
21	Q7-1	52° 30′ 16.5″	04° 13′ 16.7″	2573
22	Q8-2	52° 35′ 42.8″	04° 23′ 33.6″	2535
23	Q10-2	52° 29′ 57.6″	04° 13′ 27.9″	2337

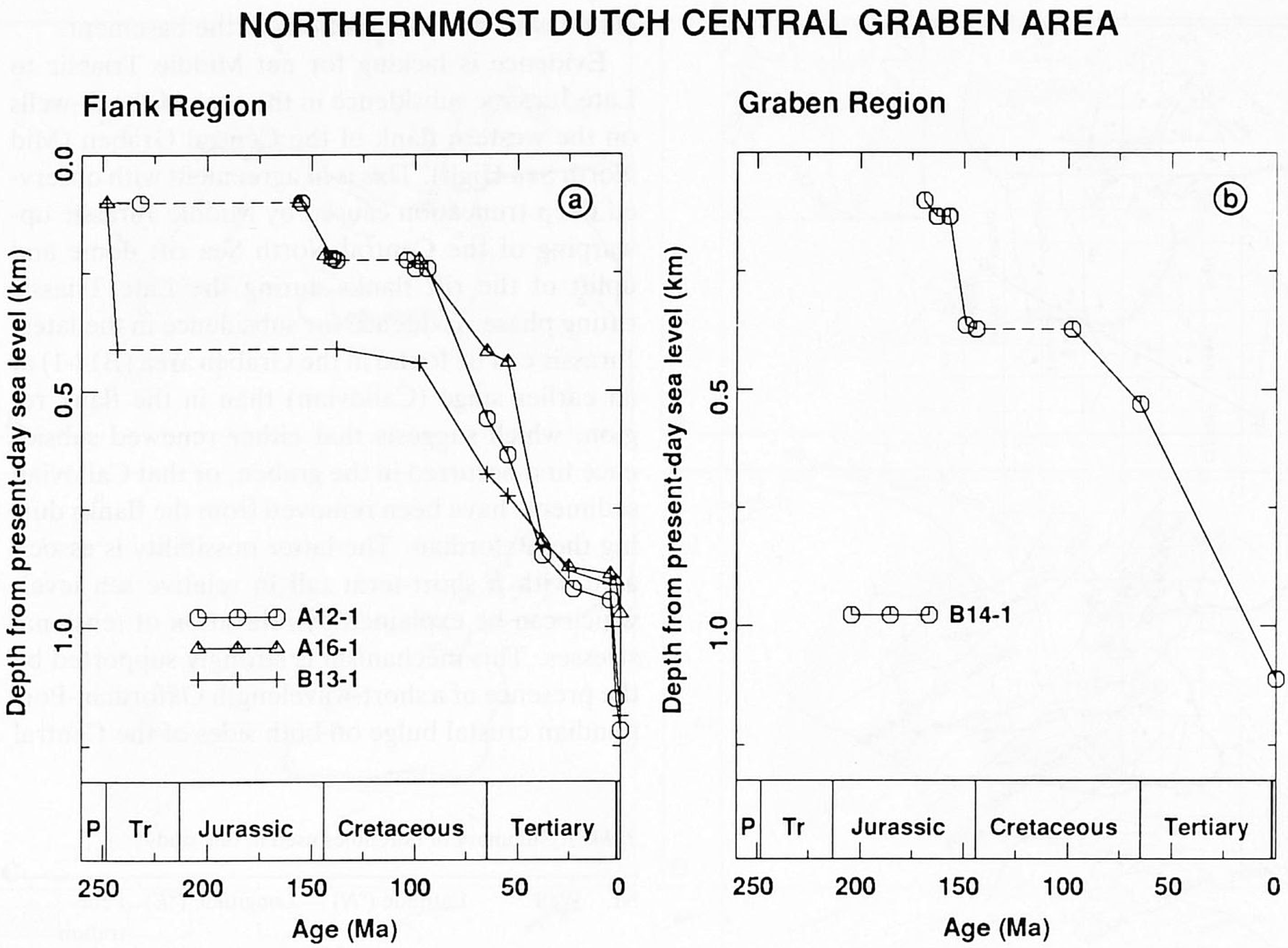


Fig. 6. Water loaded tectonic subsidence curves for four wells in the northermost part of the Dutch Central Graben. Curves have been constructed ignoring long-term changes in sea level and paleobathymetry. For location of the wells see Fig. 5 and Table 1. Wells located in the Central Graben and wells located on the flanks have been separated. Note the overall convex upward subsidence pattern of these curves.

Graben (P.A. Ziegler 1982). This phase of differential subsidence is followed by a phase of rapid subsidence corresponding to the deposition of the Kimmeridge Clay. Kimmeridgian subsidence also influenced the flanks of the graben. The B13-1 well is located on a small salt piercement and the associated salt tectonics might explain its deviating subsidence pattern. Subsidence is fairly continuous from Early Cretaceous on. For the Graben region the Late Cretacous subsidence rate appears to be relatively low. Inspection of a regional seismic NOPEC line, however, has shown that roughly half of the Late Cretaceous subsidence in the area of the B14-1 well has been compensated by salt movements, which explains the relatively low subsidence rate for this particular period inferred from the B14-1 well. Decelleration of subsidence is observed during Oligocene and Miocene times, which in turn is followed by extremely rapid subsidence during Pliocene-Quaternary times. As demonstrated by the subsidence curves for the wells in the flank region, this recent phase of subsidence is not characterized by spatially uniform subsidence rates over the area.

The absence of thick sequences of Jurassic and Early Cretaceous syn-rift sediments produces the observed overall convex upward subsidence pattern. This suggests that Jurassic and Early Cretaceous syn-rift subsidence was largely prohibited by active subcrustal heating and tectonic activity and that strong subsidence due to crustal attenuation only began after this active heating abated. On the other hand, a striking characteristic of all four wells in the northernmost part of the Dutch North Sea area is the nearly linear (post-Early Cretaceous) subsidence until mid-Tertiary times, followed by strong decelleration during Oligocene and Miocene times. This subsidence pattern deviates from the predictions of a simple thermal model for the evolution of cooling lithosphere. Although influence of active thermal processes can not be excluded, these observations create the impression that other factors have an equally important influence on the inferred subsidence characteristics.

We have investigated the effects of paleobathymetry (e.g. Gradstein et al. 1985, in press) and long-term eustatic sea level changes on the inferred tectonic subsidence. The underlying cause of long-term sea level changes (as shown in Fig. 7) is the temporal variation in thermal structure of oceanic lithosphere, which in turn is dependent on changes in the age distribution of the ocean floor. Therefore, a major control on first order sea level cycles (on the order of several tens of Ma) is the formation of new ocean basins and the destruction of preexisting ocean basins (Angevine et al. 1988). Estimates for paleobathymetry for the Cenozoic based on analysis of several wells in the Viking Graben and the Central Graben (Gradstein 1988, pers. comm.) show consistent characteristics over distances of several hundred kilometres. Apart from differences in absolute values of the inferred amplitudes, the results are largely consistent with independent paleobathymetry data for the Danish and Dutch sectors and for the central and northern part of the North Sea Basin (Barton & Wood 1984, Wood 1981). Based on these data we have constructed paleo-water depth curves for the Cenozoic, which were combined with Mesozoic data from P.A. Ziegler (1982), Frandsen et al. (1987) and Jensen & Buchardt (1987). In general, paleo-water depth estimates are subject to great uncertainties. Therefore, we have used upper limits of estimated paleo-water depths to test extreme effects of this component on the tectonic subsidence.

Fig. 8 shows the results for the analysis of the tectonic subsidence of the B14-1 well employing these paleo-water depth data and the long-term sea level curves of Kominz (1984) given in Fig. 7. Correcting for long-term sea level changes (Fig. 8a) results in net Early Cretaceous uplift, reduced Late Cretaceous subsidence and higher Cenozoic tectonic subsidence rates. Application of this correction, therefore, enhances the convex upward tectonic subsidence pattern. Adding a correction for changes in paleo-water depth (Fig. 8b) further changes the inferred subsidence pattern. Increasing water depths during Early Cretaceous yield a strong increase in tectonic subsidence. Continuing deep water conditions toward the Paleocene do not further affect the Late Cretaceous tectonic subsidence rates. More than a kilometre of sediments can be taken up in the process of net shallowing toward the present, which strongly reduces the amount of Cenozoic tectonic subsidence necessary to explain the observed sediment thickness. For comparison a synthetic tectonic subsidence curve for instantaneous depth dependent stretching (Royden & Keen 1980) at 130 Ma is shown in Fig. 8b. We adopted a crustal stretching factor $\delta = 1.17$. The subcrustal attenuation factor β controls the relative amount of initial syn-rift subsidence and thermal subsidence. We have used $\beta = 1.35$ for the construction of the synthetic tectonic subsidence curve shown in Fig. 8b. Incorporation of paleo-water depth information thus results in a concave upward subsidence pattern for low-magnitude long-term sea level

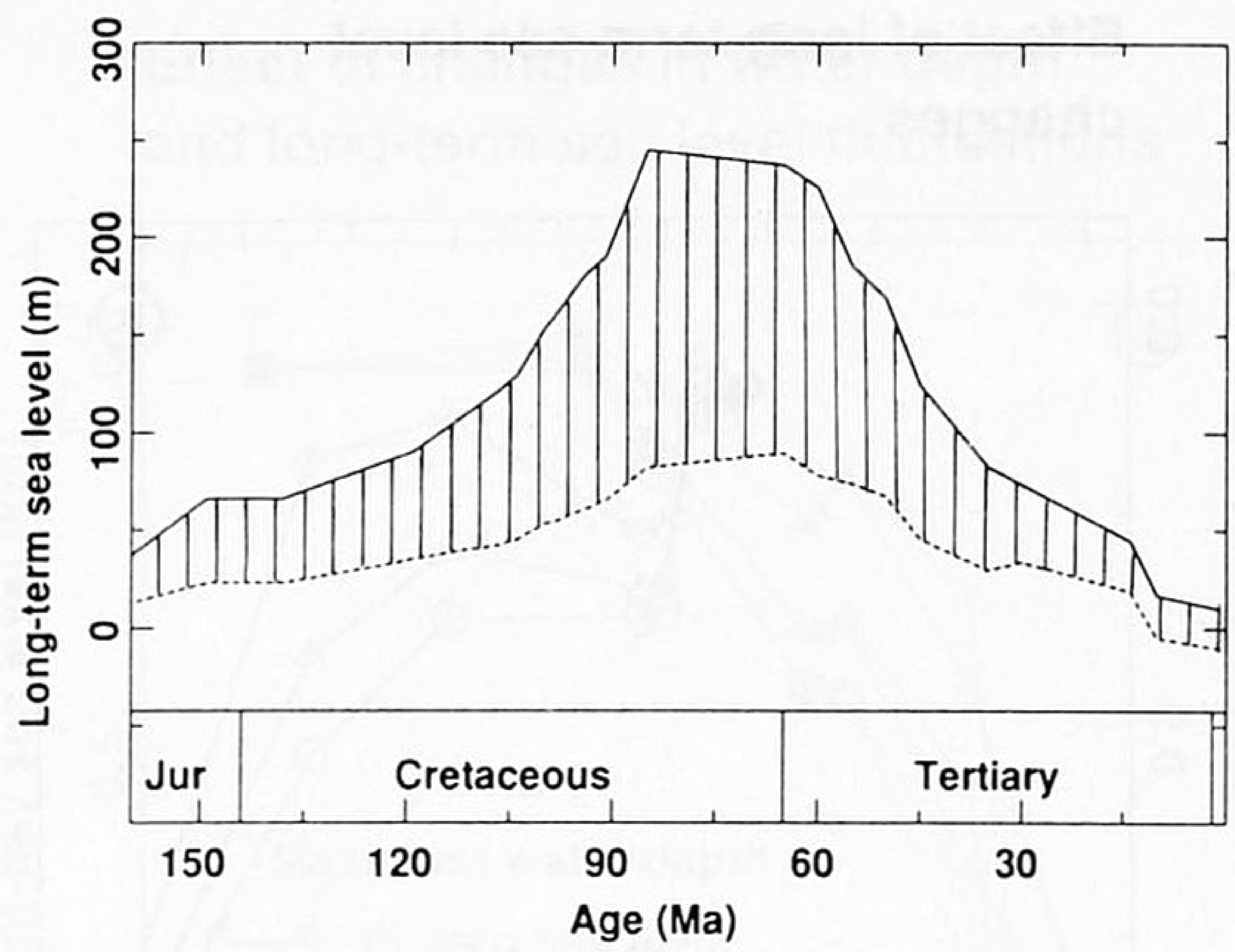


Fig. 7. Long-term sea level changes used in the analysis of two wells in the northernmost part of the Dutch Central Graben and one well in the Dutch part of the Central Graben (54° N). Continuous an dashed lines indicate maximum and minimum sea level, respectively (after Kominz 1984).

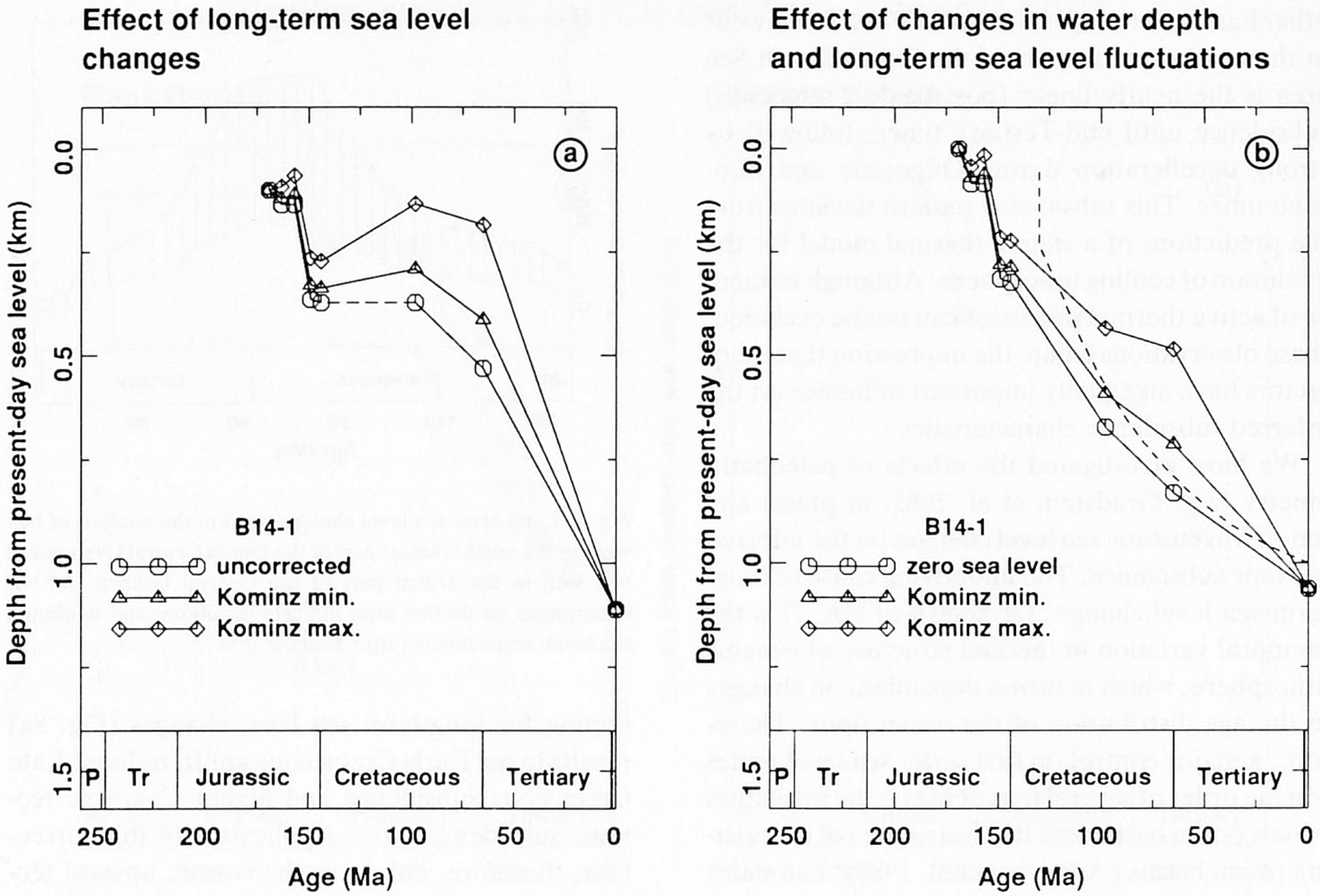
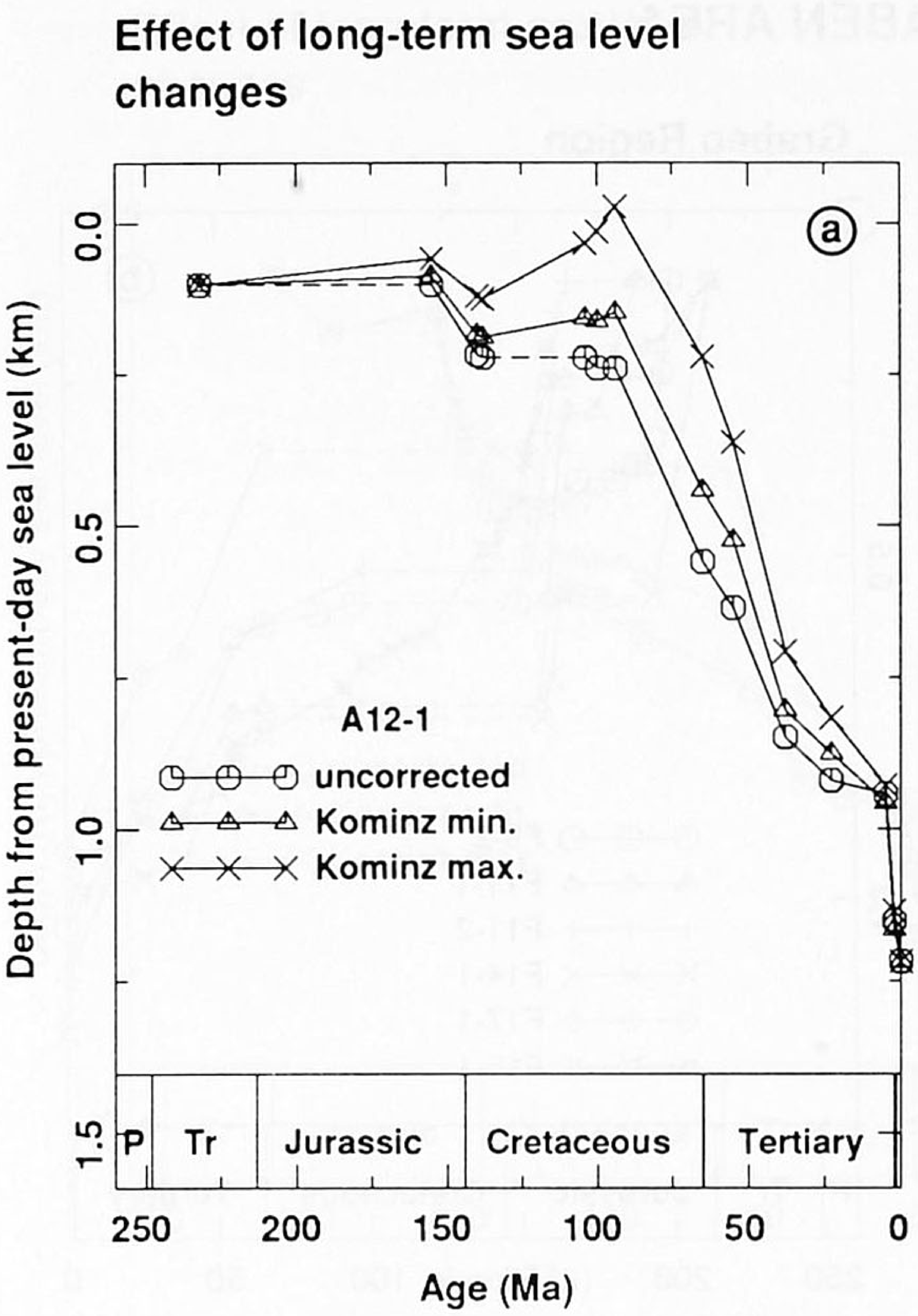


Fig. 8. Tectonic subsidence for the B14-1 well corrected for paleo-water depth and for long-term sea level changes (Kominz 1984) as indicated in Fig. 7. a) Corrected for long-term sea level changes only. The lowermost curve denotes the uncorrected tectonic subsidence. b) Corrected for both long-term sea level changes and variations in paleo-water depth. The dashed curve denotes a synthetic tectonic subsidence curve for instantaneous stretching at 130 Ma with crustal stretching by a factor of $\delta = 1.17$ and subcrustal attenuation by a factor of $\beta = 1.35$. Note the improved fit to this curve when both corrections are applied, especially for low magnitudes of the long-term sea level changes.

changes. However, the paleo-water depths used do not seem to produce the concavity predicted by a simple cooling plate model. This feature is probably caused by a lack of resolution in the Early Cretaceous part of the subsidence curve. Water depths might have been very shallow or zero near the end of the Early Cretaceous (approximately mid-Aptian), which is supported by the presence of the Early Cretaceous unconformity. Therefore, rapid subsidence might have started later than suggested by the subsidence curves of Fig. 8.

We also applied corrections for paleobathymetry and long-term changes in sea level for the A12-1 well, which contains more detailed information on Cenozoic subsidence (Fig. 9). The applied corrections for this well also give rise to dramatic modifications in the pattern of calculated tectonic subsidence. Tertiary subsidence rates are high during Paleocene and Eocene followed by uplift during Oligocene and Miocene times. This suggests that considerable differences between paleo-water depths in the northern and southern segment of this part of the North Sea Basin have occurred, especially during the Paleocene. This might be related to documented Paleocene rifting activity in the Arctic-North Atlantic domain (P.A. Ziegler 1982). Lower estimates for early Tertiary paleo-water depths give rise to a decrease in early Tertiary tectonic subsidence and at the same time reduces or nullifies middle to late Tertiary uplift (Fig. 9b).



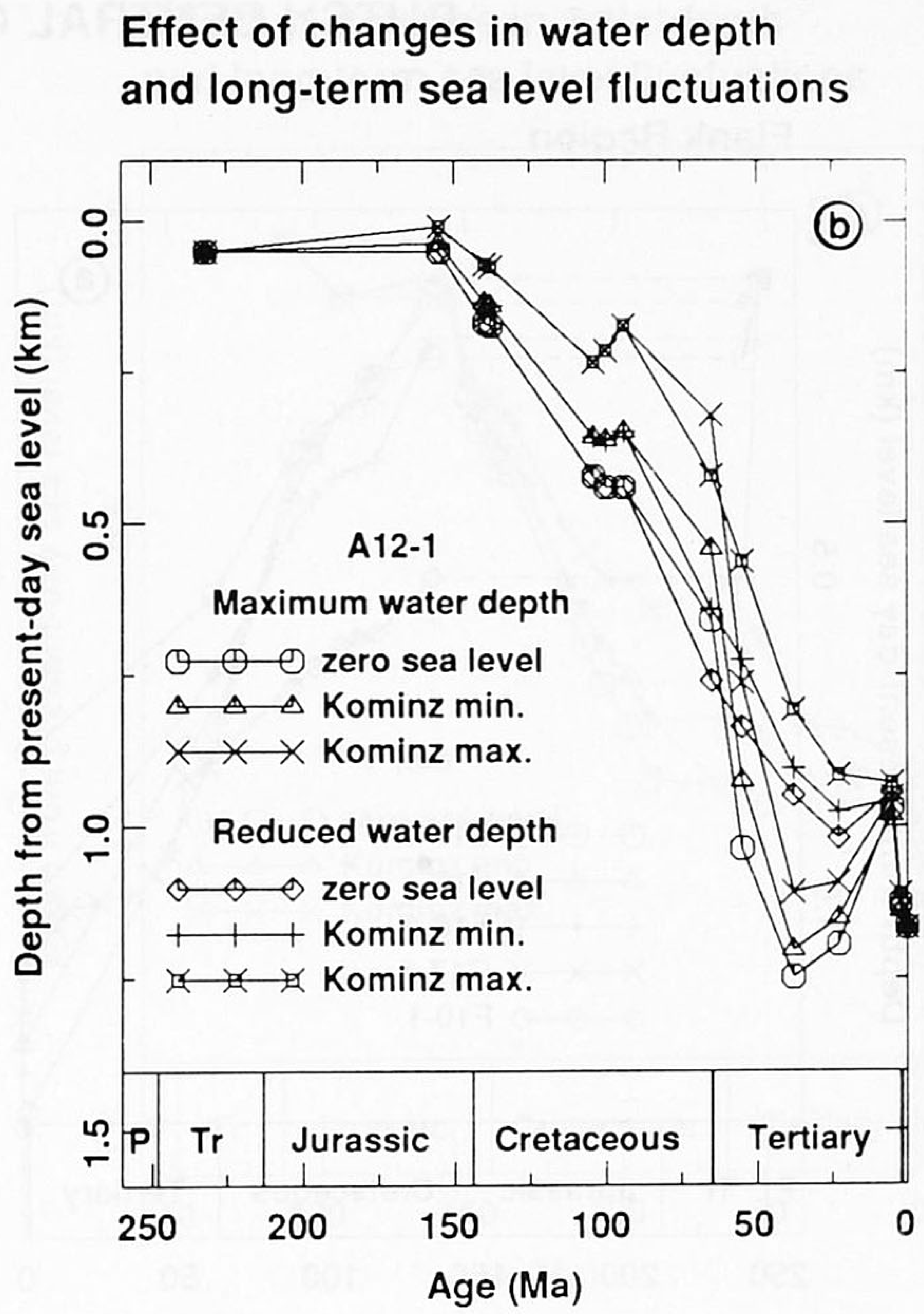


Fig. 9. Tectonic subsidence for the A12-1 well corrected for paleo-water depth variations and long-term sea level changes (Kominz 1984) as indicated in Fig. 7. a) Corrected for long-term sea level changes only. The lowermost curve denotes the uncorrected tectonic subsidence. b) Corrected for both long-term sea level changes and variations in paleo-water depth. A maximum and a reduced paleo-water depth curve have been used.

It should be kept in mind that the paleo-water depth changes used in the foregoing analysis are by their nature subject to large uncertainties. This analysis demonstrates that the interpretation of North Sea Basin stratigraphy in terms of long-term sea level changes and tectonic subsidence depends strongly on accurate information on paleo-water depths.

Central Graben area (54° North)

Stratigraphic data from eleven wells in the Dutch sector of the North Sea Basin around 54° North have been analyzed (Fig. 5). In conjunction with these well data we used a seismic NOPEC line (position indicated by BB' in Fig. 5), which traverses the Dutch Central Graben region and shows the profound effect of salt tectonics and the Laramide graben inversion in this part of the Dutch North Sea. Curves displaying the (water loaded) tectonic subsidence are given in Fig. 10.

Rapid Early and Late Jurassic subsidence is characteristic for the wells in the graben region. This phase of subsidence is the response to the Late Triassic and Middle Jurassic rifting phases. The latter phase corresponds in most wells to a period of no net subsidence or a strong decrease in subsidence rate. This feature might be associated with the uplift of the Central North Sea rift dome (P.A. Ziegler 1982). Subsequent extremely high subsidence rates during Callovian and the Oxfordian are in accordance with the observed opening of the southern part of the Central Graben during these

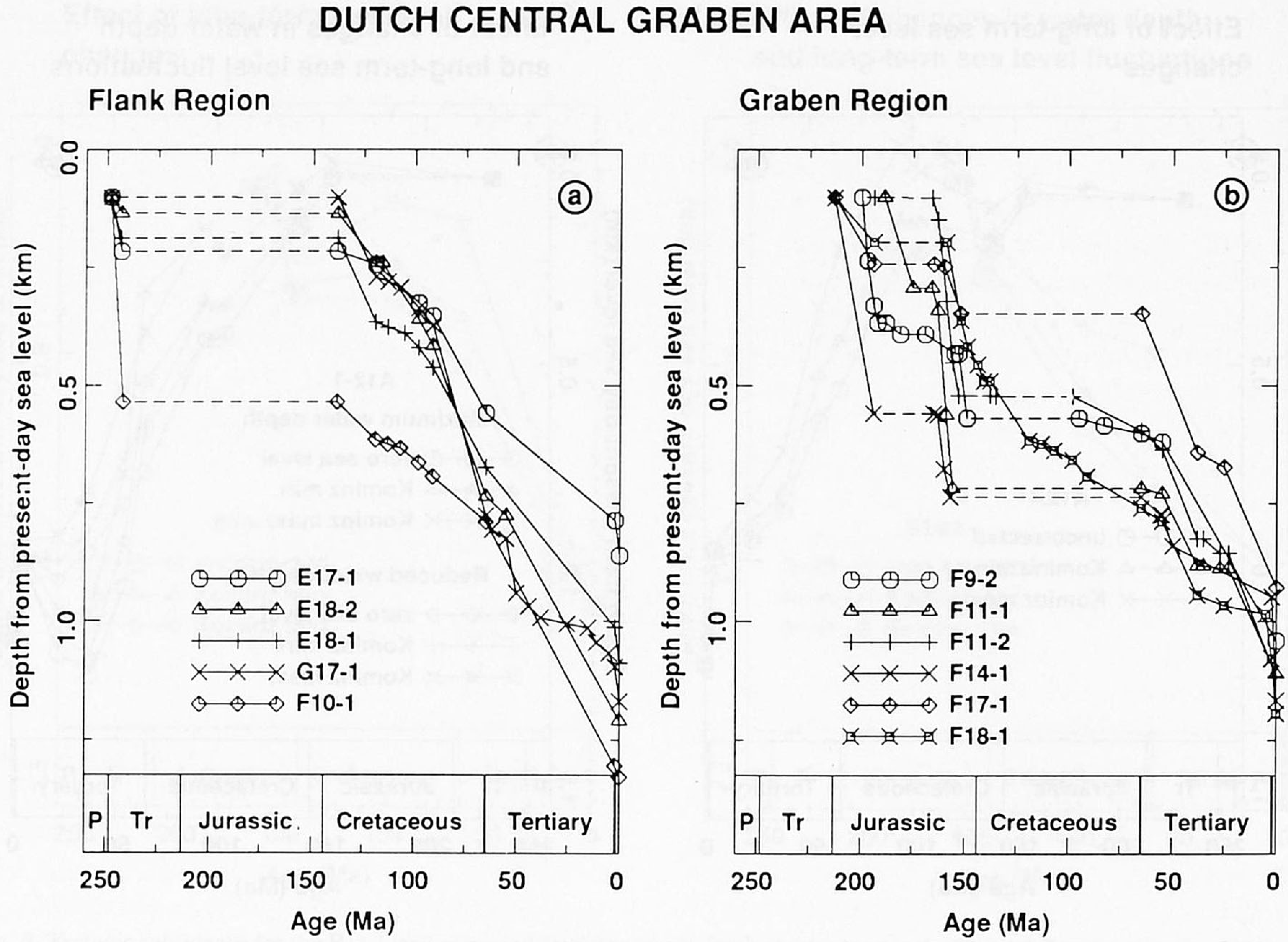


Fig. 10. Water loaded tectonic subsidence curves for eleven wells in the Dutch part of the Central Graben (54° N). For location of the wells see Fig. 5 and Table 1. Figure conventions as in Fig. 6. For the curves shown in Fig. 10 effects of long-term sea level changes and paleobathymetry have been ignored. Note the distinct differences in subsidence characteristics of these regions, indicating differential subsidence between Graben areas and flanks. Also note the overall linear to convex upward subsidence pattern displayed by these curves.

times (Herngreen & Wong 1988, this issue pp 73–105). The Cretaceous hiatuses might in part be associated with tectonic activity during the earliest Cretaceous and an increase in tectonic activity during Aptian times. To a large extent these hiatuses, however, can be attributed to deep erosion of Cretaceous and locally even Jurassic deposits caused by Senonian inversion tectonics (Heybroek 1975, P.A. Ziegler 1987). The F11-1 and F14-1 wells have been drilled on the inversion axis. The F18-1 and F9-2 wells are situated on the eastern and the F11-2 well on the western side of the inversion. The slow Late Cretaceous subsidence rates inferred from analysis of these wells might in part be due to a condensed sequence that formed in response to salt tectonics. High subsidence rates do seem to occur during early Tertiary and diminish towards the Present (well F14-1 and F18-1). These wells also show an extremely high Quaternary subsidence rate, a feature that can also be inferred for the other wells from inspection of Quaternary isopach maps (Bjorslev Nielsen et al. 1986).

The results for the wells in the flank region show remarkably coherent results (see Fig. 10). Jurassic pronounced differential subsidence of the graben and flank regions is evident. High subsidence rates on the flanks of the graben are characteristic for Cretaceous times. The timing of the initiation of this phase of Cretaceous subsidence suggests a key role of the earliest Cretaceous rifting phase in the

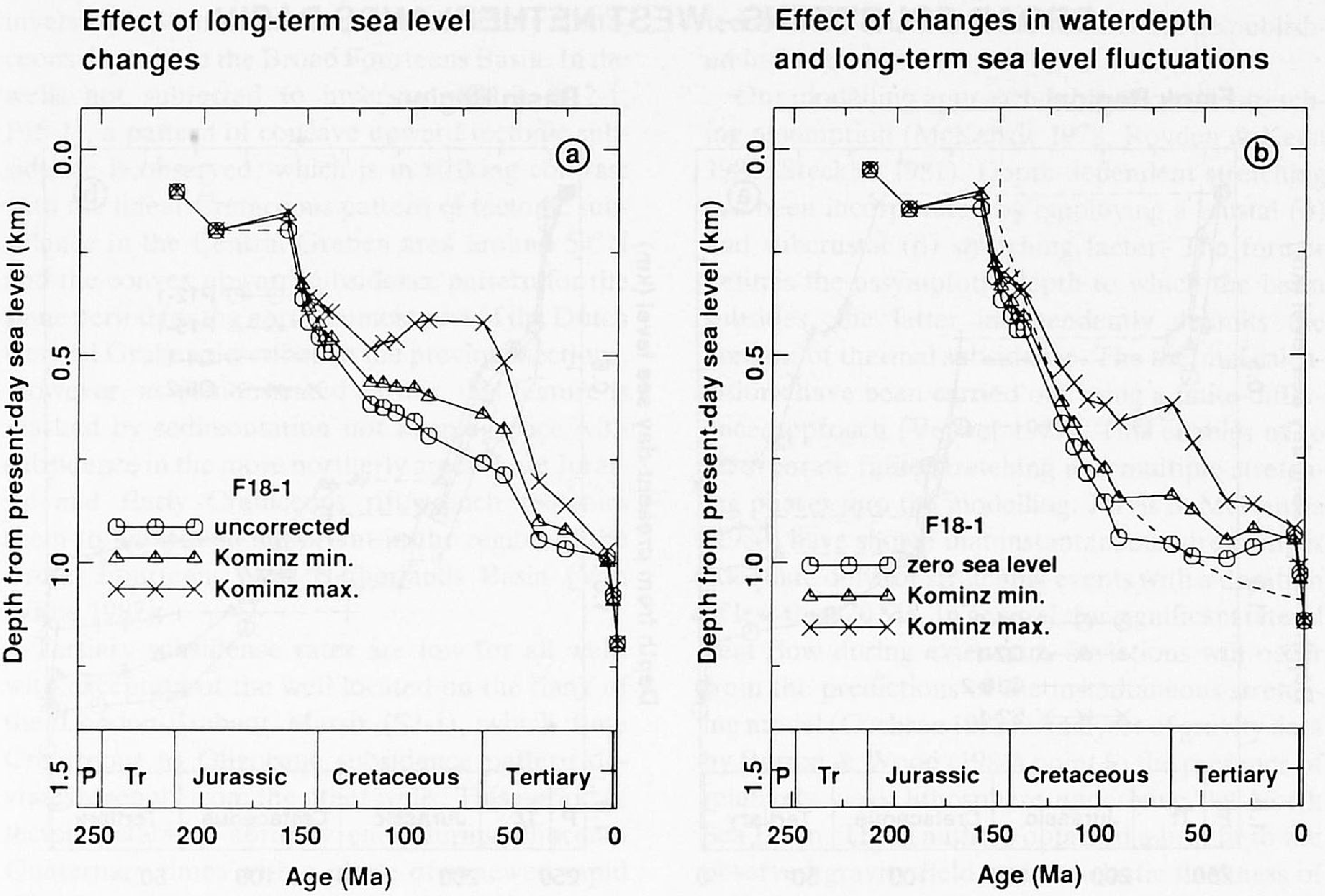


Fig. 11. Tectonic subsidence for the F18-1 well corrected for paleo-water depth fluctuations and long-term sea level changes (Kominz 1984) as indicated in Fig. 7. a) Corrected for sea level changes only. The lowermost curve denotes the uncorrected tectonic subsidence. b) Corrected for both long-term sea level changes and variations in paleo-water depth. The dashed curve denotes a synthetic tectonic subsidence curve for instantaneous stretching at 150 Ma with crustal stretching by a factor of $\delta = 1.2$ and subcrustal attenuation by a factor of $\beta = 1.4$. Correction for both low magnitude long-term sea level changes and variations in paleobathymetry yields a subsidence pattern which closely resembles predictions from thermal models.

subsidence history of the area.

We have incorporated paleo-water depth data and the long-term sea level curves from Kominz (1984) in the subsidence analysis of the F18-1 well (Fig. 7). Again low-magnitudes for long-term sea levels, combined with conservative estimates of paleo-water depths yield a relatively good fit to a synthetic tectonic subsidence curve for instantaneous crustal stretching at 150 Ma with $\delta = 1.2$ and subcrustal attenuation with $\beta = 1.4$ (Fig. 11). Strong deviations from the thermally induced subcidence can be observed for the Pliocene and the Quaternary.

The analysis of the well data for the Dutch Central Graben area (54° N) has shown the great impact of the Late Jurassic and probably Early Cretaceous rifting phases on the subsidence history of this region. Inspection of the subsidence curves given in Figs. 10 and 11 shows that the wells on the flanks and in the Graben each have distinctly characteristic and different subsidence histories.

Broad Fourteens/West Netherlands Basins

The location of eight wells located along a NNE-SSW trending line crossing the Broad Fourteens Basin and the western part of the West Netherlands Basin is given in Fig. 5. The tectonic subsidence curves reconstructed from these well data are dis-

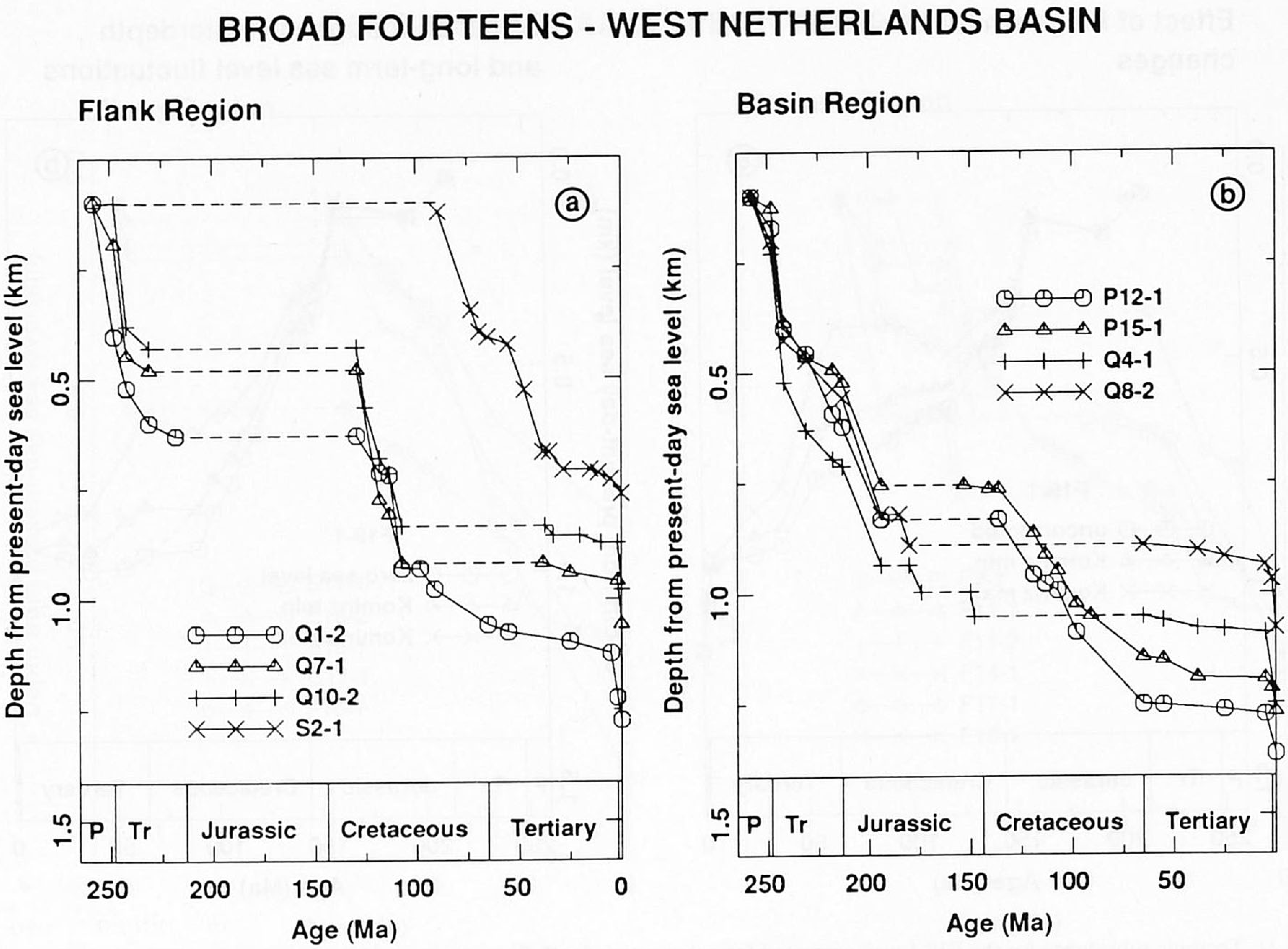


Fig. 12. Water loaded tectonic subsidence curves for eight wells in the Broad Fourteens and West Netherlands Basins. For location of the wells see Fig. 5 and Table 1. Wells located in the deepest parts of the basins are displayed separately from the wells located on the flanks. Figure conventions as in Fig. 6. For the curves shown in this figure effects of long-term sea level changes and paleobathymetry have been ignored. Note the overall (stepwise) convex downward subsidence pattern.

played in Fig. 12. Similarly to the procedure outlined in the previous sections we have differentiated between well data from the flanks and the basin interiors. Most of the subsidence curves demonstrate tectonic subsidence since the beginning of the Late Permian, which corresponds to the initiation of the Zechstein basin. The progressively northward increase in the thicknesses of Zechstein deposits is reflected in the subsidence curves. This period is followed by very high subsidence rates during Early Triassic to Late Jurassic. As described in the previous two sections, a similar phase of rapid Early Triassic subsidence has been observed for the flank region of the Central Graben (B13-1, F10-1). These high subsidence rates attest to the rift-stage character of the southern North Sea Basin at these times. Subsidence characteristics are apparently uniform in all wells during Permo-Triassic times and probably also during the earliest Jurassic. An important erosional phase has removed much of the Jurassic, and earliest Cretaceous subsidence record from basin interiors and has even truncated Triassic deposits from the adjacent highs. Interruptions of these periods of no net subsidence are observed in the Q4-1 and Q8-2 wells (located in the Broad Fourteens Basin) with evidence of minor, but fast, Aalenian and Kimmeridgian subsidence.

Following the Early Cretaceous rifting phase, renewed subsidence has occurred in the West Netherlands Basin (P-wells). At the same time Late Cretaceous and early Tertiary phases of basin inversion have truncated much of the Early Cretaceous deposits in the Broad Fourteens Basin. In the wells not subjected to inversion (Q1-2, P12-1, P15-1), a pattern of concave upward tectonic subsidence is observed, which is in striking contrast with the linear Cretaceous pattern of tectonic subsidence in the Central Graben area around 54° N and the convex upward subsidence pattern for the same period for the northernmost part of the Dutch Central Graben described in the previous sections. However, as demonstrated earlier, this feature is masked by sedimentation not keeping pace with subsidence in the more northerly areas. Late Jurassic and Early Cretaceous rift/wrench tectonics seem to have been important in the region of the Broad Fourteens/West Netherlands Basin (Van Wijhe 1987).

Tertiary subsidence rates are low for all wells with exception of the well located on the flank of the London-Brabant Massif (S2-1), which Late Cretaceous to Oligocene subsidence pattern deviates strongly from the other wells. This period of tectonic stability abruptly ends during Pliocene-Quaternary times with a phase of renewed rapid subsidence which can be observed for all wells.

The timing of the main subsidence phases for the Triassic, Jurassic and earliest Cretaceous as inferred from the wells from the Broad Fourteens/West Netherlands Basins is in accordance with the findings for the Central Graben area described in the two previous sections. On the other hand, conspicuous differences exist from one region to another for Cretaceous and Tertiary subsidence. The overall subsidence characteristics shown in the foregoing analysis of well data provide useful constraints for the stratigraphic modelling of North Sea Basin stratigraphy presented in the following section.

Stratigraphic modelling

In this section, we discuss models for the stratigraphy of the northernmost transect described in the quantitative subsidence analysis of the well data (see Fig. 5). Stratigraphic modelling for the southern part of the Central Graben, the Broad Fourteens and West Netherlands Basins will be published in future work.

Our modelling approach is based on the stretching assumption (McKenzie 1978, Royden & Keen 1980, Steckler 1981). Depth-dependent stretching has been incorporated by employing a crustal (δ) and subcrustal (β) stretching factor. The former defines the assymptotic depth to which the basin subsides, the latter independently delimits the amount of thermal subsidence. The thermal calculations have been carried out using a finite-difference approach (Verwer 1977). This enables us to incorporate finite stretching and multiple stretching phases into the modelling. Jarvis & McKenzie (1980) have shown that instantaneous stretching is adequate only for stretching events with a duration of less than 20 Ma. In general, for significant lateral heat flow during extension, deviations will occur from the predictions of the instantaneous stretching model (Cochran 1983). Analyses of gravity data by Barton & Wood (1984) point to the presence of relatively weak lithosphere underlying the North Sea Basin. These authors obtained a best fit to the observed gravity field with an elastic thickness of only 5 kilometres. Thorne (1986) obtained estimates for the effective elastic thickness varying between 8 and 25 kilometres for several periods during the Cretaceous and Cenozoic. Such low estimates for flexural rigidities are not unusual for basins located on continental lithosphere. Detailed analysis of the northern Canadian Sverdrup Basin has yielded estimates of the equivalent elastic thickness of less than 30 km (Stephenson et al. 1987). In contrast, estimates of equivalent elastic thicknesses of old oceanic lithosphere are characteristically of the order of 40–50 km (McAdoo et al. 1985). In our modelling of North Sea subsidence we have adopted a value of 10 km for the effective elastic thickness of the lithosphere. Compaction is calculated according to an exponential porosity-depth relation (Sclater & Christie 1980)

$$\varphi(z) = \varphi_0 e^{-cz} \qquad (1)$$

where φ_0 and c denote the surface porosity and the decay constant respectively.

A structural cross-section published by P.A. Zie-

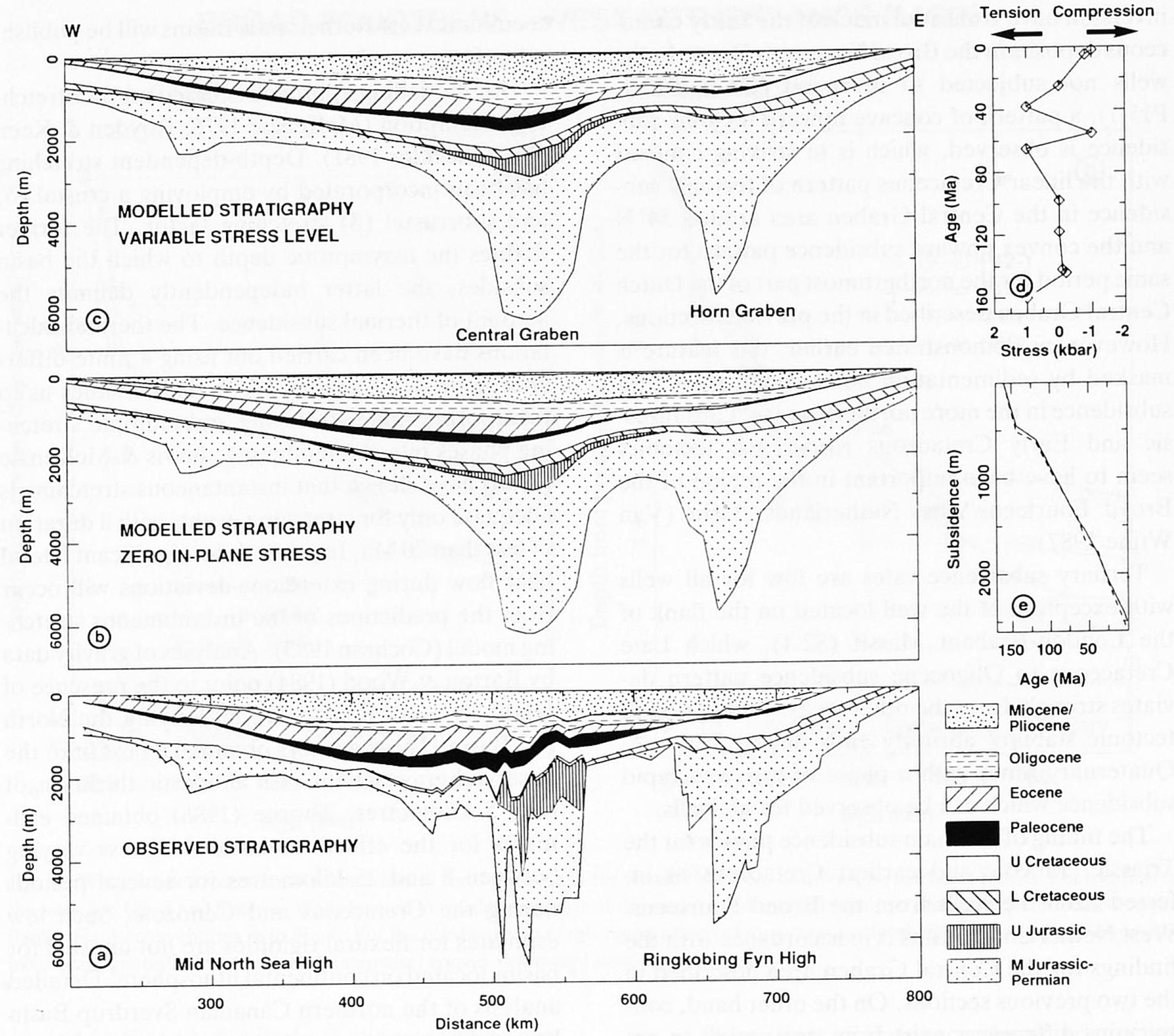


Fig. 13. Stratigraphic modelling for the transect through the northernmost part of the Dutch Central Graben. Location shown in Fig. 5 as AA'. a) Documented stratigraphy (after P.A. Ziegler 1982). The pre-Quaternary stratigraphy has been restored by removing the thick Quaternary deposits from the original section by P.A. Ziegler (1982). Note the great thickness of Tertiary deposits relative to the amount of Cretaceous sediments. b) Best fit to observed stratigraphy obtained in the absence of intraplate stress changes. The basin created by the subsidence due to thermal contraction and crustal thinning is flexurally filled with sediments. c) Modelled stratigraphy for changes in intraplate stress level displayed in Fig. 13d. Note the absence of Paleocene sediments over the horst separating the two graben systems and a phase of Eocene offlap. d) The intraplate stress pattern inferred from the stratigraphic model displayed in Fig. 13c. e) Basement subsidence amplified by sediment and water loading in the graben plotted as a function of age at the 540 km location in Figs. 13b, c. Solid curve denotes the subsidence in the absence of intraplate stress changes. Dashed curve indicates the subsidence for a variable stress level.

gler (1982) with a length of 600 kilometres from Denmark towards the British coast is shown in Fig. 13a. This section cuts through the Ringkobing-Fyn and Mid North Sea High and traverses the Danish Central Graben and the Horn Graben. The Cenozoic basin displays both onlap and offlap phases. The cross-section does not show differential compaction over the basement highs and lows, which is predicted when using porosity-depth relations from Bond & Kominz (1984). This might be an indication of either an overestimate of the amount of porosity reduction due to compaction, or overpressuring of the graben sediments. For reasons of convenience we adopted the former possibility and employed a surface porosity φ_0 of 25% and a decay constant c of 0.1 km^{-1}. Strictly speaking, modelling of the pre-Cretaceous basin would require a model of graben formation and fault tectonics. In the present study we did not incorporate the effects of faulting in our thermo-mechanical models. As the present work focuses on the Cretaceous and Tertiary basin, this seems to be a reasonable simplification. Forthcoming, more detailed, numerical modelling of the Mesozoic stratigraphy will explore the effect of faulting on basin stratigraphy.

As shown in the analysis of the well-data, negligence of corrections for paleobathymetry would result in concave downwards tectonic subsidence curves for this region. Hence, ignoring these variations in paleobathymetry in forward modelling would require either periods of active stretching near the end of Cretaceous times or delayed subsidence due to active subcrustal heating during the Cretaceous. However, incorporation of changes in paleo-water depth in the analysis of the well-data produces a tectonic subsidence pattern which is more in accordance with a period of stretching activity during Late Jurassic and probably also Early Cretaceous. We have assumed this period of stretching to extend from Callovian (163 Ma) to Aptian (119 Ma) and ignored the thermal subsidence due to Mid-Jurassic and Triassic periods of extension. The latter assumption results in an overestimate of the amount of crustal thinning (Hellinger et al. in press). As Late Jurassic sediments are mainly confined to the Central Graben, we assumed the Jurassic period of stretching (163–144 Ma) to have affected primarily the crust, without inducing much thermal subsidence. The Cretaceous period of stretching (144–119 Ma) has been taken as the period of more extensive lithospheric thinning.

The Quaternary basin forms a problem on its own. Up to 1000 metres of Quaternary sediments are present in the North Sea area (Bjorslev Nielsen et al. 1986), a thickness that is comparable to the thickness of Miocene-Pliocene deposits. The associated acceleration in subsidence can not be accounted for by filling of pre-existing bathymetric lows and must therefore be associated with an acceleration in tectonic subsidence. Such short-term phases of rapid subsidence are not limited to the North Sea Basin and are a feature commonly observed in pull-apart basins, such as the Neogene Californian basins with documented subsidence rates of the order of a few km/Ma (Christie-Blick & Biddle 1985, Pitman & Andrews 1985). The present analysis concentrates on the pre-Quaternary basin evolution, as better constraints on the origin of the Quaternary basin are required to discriminate between several potential models for Quaternary North Sea Basin subsidence.

We have simulated the presence of the Central and Horn Graben by incorporating pre-existing isostatic depressions in the models. This approach probably implies an overestimate of the flexural component of the basement response but allows us to account for compaction of the sediments that fill in the graben. Inspection of Fig. 13a shows that Early Cretaceous deposits are absent or very thin on the Mid North Sea High and the Rynkobing Fyn High. The environment of deposition for much of the Early Cretaceous deposits, especially for the Danish sector, indicates relatively deep-marine conditions as exemplified by mass flow deposits and mid-Early Cretaceous pelagic carbonates (Frandsen et al. 1987, Jensen & Buchardt 1987). At the same time, much of the Rynkobing Fyn High and parts of the Mid North Sea High were subaerially exposed during Berriasian to Barremian times (P.A. Ziegler 1982). The latter indicates a lack of tectonic subsidence. As mentioned previously, subcrustal attenuation can be used to independently delimit the amount of lithospheric heating. We employed this mechanism to constrain the amount of Early Cretaceous syn-rift sediments and adopted a maximum paleo-water depth of 70 metres at early Aptian. On the other hand, restriction of the thickness of post-rift Aptian, Albian and Late Cretaceous sediments in the modelling is a consequence of an increase in paleo-water depth. We employed a maximum paleo-water depth of 470 metres. This increase in paleo-water depth compensates for both the rapid thermal subsidence following the rifting phase and for a long-term rise in sea level. For the latter we adopted the minimum curve from Kominz (1984) (see Fig. 7). Subsequently, for the modelling of the Tertiary basin we incorporated gradual shallowing towards Quaternary times. These water depths conform reasonably well with the paleo-water depths used in the subsidence analysis of the well-data.

Fig. 13b shows our preferred model derived in the absence of intraplate stress changes. The total crustal stretching used in the modelling has a maximum (δ) of 1.2 in the Central Graben and decreases rapidly towards the basin edges (Table 2). Integration of these stretching factors yields a mean crustal extension of 9% for this cross-section, which corresponds to roughly 60 kilometres. This value is probably an overestimation of the total post-Mid-Jurassic extension due to the ongoing thermal subsidence of previous stretching events (Hellinger et al.

Table 2. Stretching factors.

Position (km)	β	δ
200	1.25	1.05
240	1.25	1.06
280	1.35	1.07
310	1.41	1.08
340	1.44	1.09
350	1.47	1.10
370	1.47	1.11
380	1.47	1.12
390	1.49	1.13
400	1.60	1.13
410	1.70	1.14
450	1.71	1.15
470	1.73	1.16
510	1.73	1.16
520	1.73	1.17
530	1.63	1.20
540	1.63	1.20
550	1.53	1.16
560	1.43	1.12
610	1.43	1.10
680	1.44	1.09
730	1.41	1.08
750	1.35	1.07
760	1.30	1.06
780	1.25	1.05
790	1.18	1.04
800	1.05	1.02

in press) and possible contibutions from physicochemical processes affecting the density of the crust. For most of the section pre-Late Jurassic sediments are not very thick due to deep Mid-Jurassic erosion, which is associated with the uplift of the Central North Sea rift dome (P.A. Ziegler 1982). Therefore, the stretching parameters used in the modelling also account for at least a large part of the subsidence due to previous Triassic to Mid-Jurassic extension.

A substantially better fit to the observed stratigraphy can be obtained by incorporating fluctuating intraplate stress levels in the analysis (Fig. 13c). The stress-induced differential vertical movements strongly enhance the quality of the modelling of details of the stratigraphy. The intraplate stress pattern inferred from the stratigraphic modelling is characterized by Late Jurassic to Teriary tensional and neutral stress levels followed by compressive stresses during Tertiary times (Fig. 13d). Superimposed on this long-term trend are fluctuations in stress level of a shorter duration. Synthetic subsidence curves for the base Upper Jurassic (Fig. 13e) demonstrate the characteristic stress-induced short-term deviations from the long-term subsidence predicted by thermal models of basin evolution. The paleo-stress levels vary from 1 kbar tension in Callovian, Early Paleocene and Early Oligocene to 1 kbar compression at Early Eocene and Quaternary. These are stress levels throughout the basin profile, as a uniform plate thickness has been used in the modelling. These changes in intraplate stress levels in the modelled cross-section can be induced by either a rotation of the stress field, or by changes in the magnitude of the principal stresses. The local effects of the horst and the grabens are evident. Late Jurassic relaxation of tension has removed part of the Late Jurassic sediments from the flanks of the Central Graben and has produced an erosional unconformity. Similarly, a change from a tensional to a compressional stress regime during the Paleocene induces downwarping of the grabens and uplifting of the intervening horst. The subsequent release of compression in the Eocene has the opposite effect, resulting in a relatively thin package of Eocene deposits in the Central Graben. The Tertiary stress

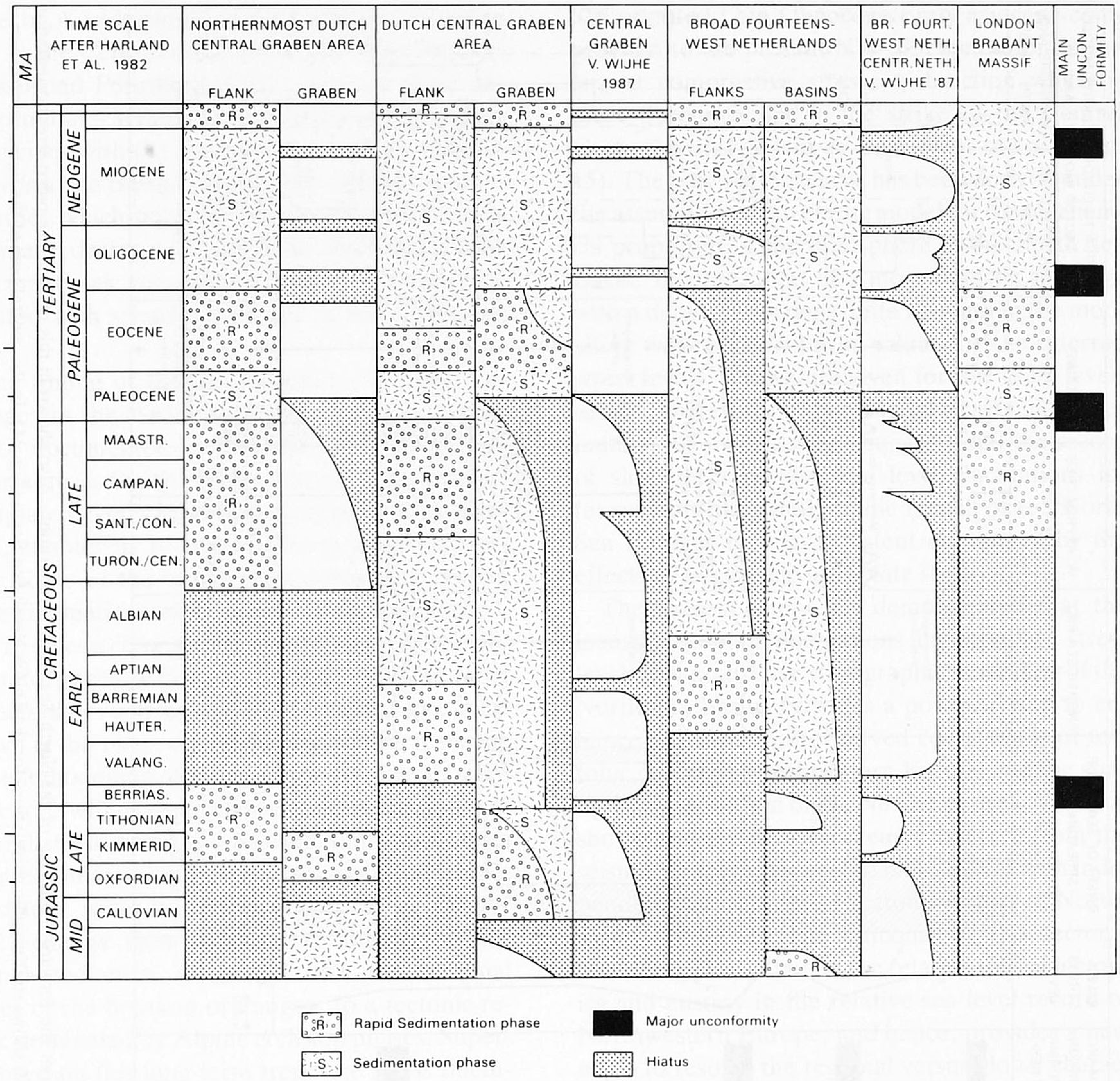


Fig. 14. Stratigraphic correlations for the well data used in this study supplemented with stratigraphic compilations made by Van Wijhe (1987). Hiatuses have been correlated to infer the main unconformities for the Dutch North Sea Basin. Similarly, main phases of rapid sedimentation and normal/slow rate sedimentation have been indicated. The column on the right gives the results of the correlation.

pattern inferred from the stratigraphic modelling is relatively well-constrained. The Cretaceous paleostress pattern is subject to larger uncertainties, a feature that is inherent to less stratigraphic resolution for this particular time slice. The numerical values of the stresses are dependent on rheological properties of the lithosphere under the North Sea Basin and give therefore the order of the stress magnitudes.

Discussion and conclusions

Figure 14 summarizes the timing of sedimentation phases and the periods characterized by hiatuses and unconformities in the Dutch part of the North Sea. Comparison of the overall stratigraphy inferred from this study supplemented with the outcome of earlier work by Letsch & Sissingh (1983) and Van Wijhe (1987) demonstrates the occur-

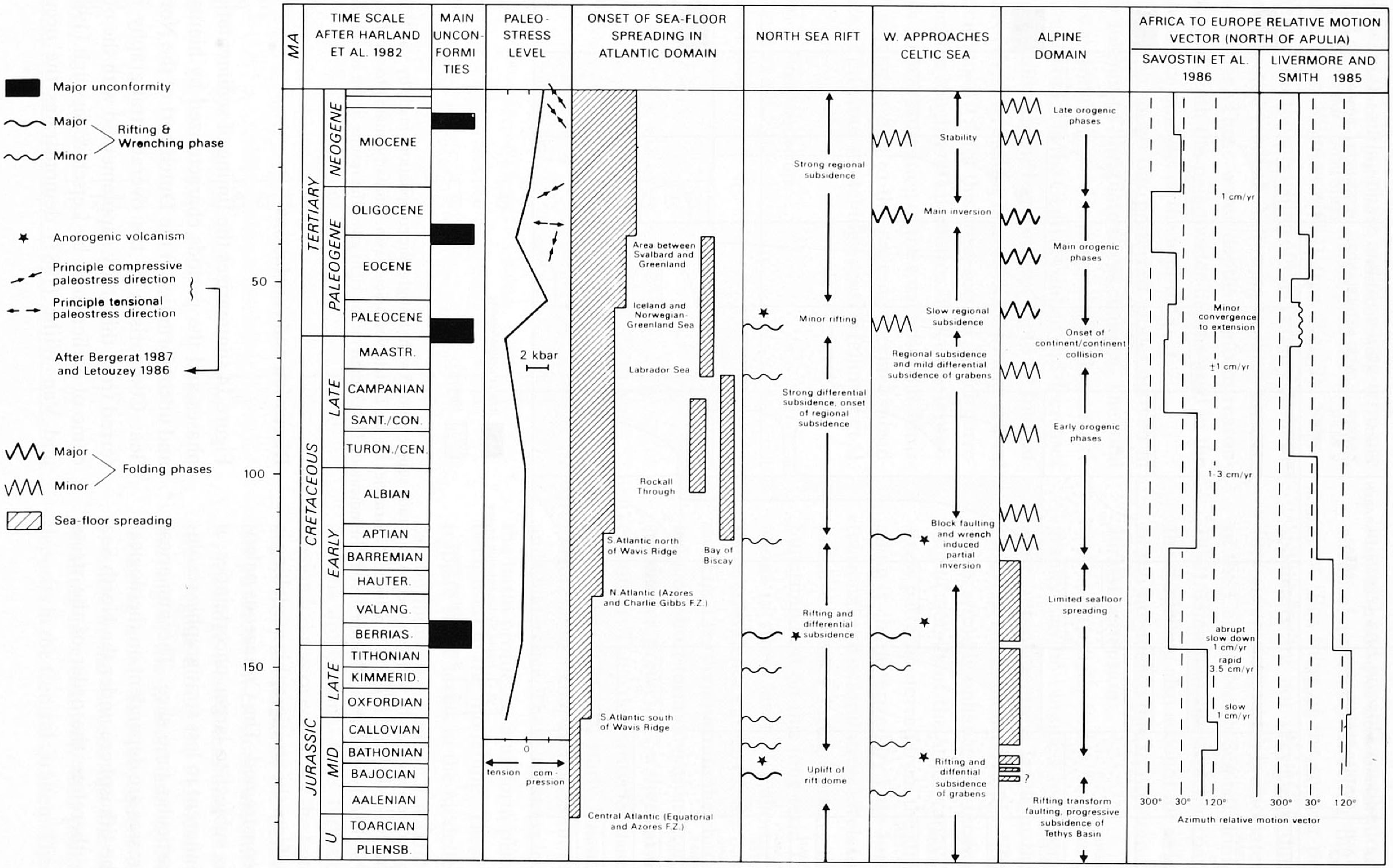


Fig. 15. Synthetic paleo-stress curve as inferred from the forward modelling of the North Sea Basin stratigraphy. Also shown in this column are paleo-stress orientation data from Bergerat (1987). The column on the far left shows stratigraphic correlations for the Dutch North Sea Basin (Fig. 14). In the central part of the figure information is displayed on the timing of onset of sea-floor spreading in the Atlantic domain and timing of tectonic events in the North Sea rift, the Western Approaches/Celtic Sea and in the Alpine domain (after P.A. Ziegler 1982). The columns on the right show Africa relative to Europe plate motion data after Savostin et al. (1986) and Livermore & Smith (1985).

rence of 4 widespread unconformities occurring both in the Central Graben and the West Netherlands/Broad Fourteens Basins. One of these unconformities – at the Jurassic/Cretaceous boundary – coincides with the timing of a stretching phase in the North Sea Basin. The other three major unconformities which occur at the Cretaceous/Tertiary boundary, during mid-Oligocene times and at Late Miocene times, respectively cannot be directly associated with stretching phases in the North Sea area.

The timing of the unconformities is related to changes in the Africa to Europe relative motion vector documented by Savostin et al. (1986) and Livermore & Smith (1985). The incorporation of intraplate stresses in stratigraphic modelling, however, enables us to explore the dynamics underlying some of the observed correlations between plate kinematics and the apparent sea level record. Fig. 15 gives a comparison of the timing of the main unconformities with P.A. Ziegler's (1982) timing of tectonic events in Northwestern Europe. Also shown is the paleo-stress curve resulting from the present modelling of the stratigraphy. The trend of the curve with a change from overall tension and neutral stresses during Mesozoic times to a stress regime of more overall compressional character is consistent with the documented (P.A. Ziegler 1982) change from a Mesozoic regime of rift/wrench tectonics, associated with the terminal stages of the breakup of Pangea, to a tectonic regime dominated by Alpine collision phases. Superimposed on this long-term trend are stress fluctuations of a shorter period. The paleo-stress curve of Fig. 15 displays a strong phase of compression during Early Eocene times corresponding in timing with the occurrence of strong folding phases in the Alpine domain. For Late Eocene to Early Oligocene we predict a stress regime of more tensional character, concomittant with the timing of initiation of rifting in the European platform, and an associated observed tensional paleo-stress field (Letouzey 1986, Bergerat 1987). The predicted overall increase in the level of the post-Early-Oligocene compression is consistent with the observed (Letouzey 1986, Bergerat 1987) rotation of the paleo-stress field in Northwestern Europe from NE-SW oriented Late Oligocene/Early Miocene compression to the present NW-SE orientation of the largest compressive stress, a direction which is more perpendicular to the strike of the Central Graben basins (Klein & Barr 1986, see also Fig. 15). The paleo-stress curve has been derived under the assumption of an elastic model for the mechanical properties of the lithosphere in the North Sea Basin. Incorporation of a more realistic rheology with a depth-dependent finite strength in the modelling will result in lower values for the inferred stress levels. The values given for the stress levels should, therefore, be considered to provide upper limits. Our work strongly suggests that the record of short-term relative sea level fluctuations inferred from the stratigraphic record of the North Sea Basin is to a large extent dominated by the effects of large-scale intraplate stresses.

The present study has demonstrated that the incorporation of fluctuations in intraplate stress levels in quantitative stratigraphic modelling of the North Sea Basins provides a powerful tool to enhance our insight in observed correlations of tectonic events in Northwestern Europe and the stratigraphic evolution of the North Sea area. We have shown that a paleo-stress curve inferred from the seismic stratigraphic record is consistent with independent data sets on the tectonic history of Northwestern Europe. The outcome of this tectonic modelling sheds light on the relative role of tectonics and eustasy in the relative sea level record of Northwestern Europe, and hence, provides a new angle to resolve the regional versus global character of Vail's short-term sea level changes. Our findings suggest that tectonics might dominate the apparent sea level record, even during periods with a non-ice free world.

Acknowledgements

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