# Intraplate stresses: A new tectonic mechanism for fluctuations of relative sea level

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## ABSTRACT

**Stress variations in the lithosphere of a few hundred bars can explain the major part of the seismostratigraphic record at passive margins and intracratonic basins. However, to induce apparent sea-level fluctuations with magnitudes greater than 50 m, changes in stress level of more than 1 kbar are required. These must be related to major reorganizations at convergent plate boundaries, fragmentation of plates, or collision processes. Specific rapid falls in the Vail et al. curves can be associated quantitatively with particular plate-tectonic reorganizations of lithospheric stress fields. The seismostratigraphic record may provide a new source of information on paleo-stress fields to be correlated with results of independent numerical modeling of intraplate stresses.**

## INTRODUCTION

Recently Cloetingh et al. (1985a, 1985b) proposed a new tectonic mechanism for regional sea-level variations of about 1–10 cm/1000 yr, having a magnitude of up to a few hundred metres. Their model explains these changes, provided that horizontal stresses of the order of a few kilobars exist in the lithosphere and changes in these stress fields occur on geologic time scales. The proposed model represents the interaction between these stresses and the deflections of the lithosphere caused by sedimentary loading (Fig. 1). Apparent sea-level changes of more than 100 m can be produced at the flanks of sedimentary basins by this interaction. Therefore, Cloetingh et al. (1985a, 1985b) pointed out that glacial fluctuations (Pitman and Golovchenko, 1983) are not the only mechanism capable of producing apparent sea-level changes in excess of 1 cm/1000 yr as well as magnitudes of about 100 m.

New evidence from studies of Oligocene-Miocene carbon isotope cycles and abyssal circulation changes (Miller and Fairbanks, 1985) and from modeling subsidence at the United States passive margin (Watts and Thorne, 1984) has provided revised quantitative estimates for the magnitude of the mid-Oligocene fall in sea level. The magnitude of the mid-Oligocene lowering in sea level, by far the largest of the falls in sea level shown in the Vail et al. (1977) curves, is estimated by Miller and Fairbanks (1985) and Watts and Thorne (1984) to be at most 50–60 m. Thorne and Bell (1983) derived a eustatic sea-level curve from histograms of North Sea subsidence that is also consistent with lower estimates of the amplitude of the sea-level changes. Furthermore, Vail et al. (1984) no longer equate relative changes of coastal onlap with relative changes of sea level. The modified Vail et al. (1984) curve for the Jurassic sea levels has kept the same overall form as the original coastal onlap and offlap curve, with an overall reduction of the magnitude and with some of the corresponding sea-level changes being more symmetrical. These findings have led me to explore here the consequences of the possibility that the majority of sea-level falls inferred from seismostratigraphy have a characteristic magnitude of only a few tens of metres within a time interval of a few million years (Aubry, 1985; Schlanger, 1986). The outcome of this study is important in connection with the magnitude and rate of the underlying variations in intraplate stresses.

## INTRAPLATE STRESS FIELDS

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 stresses may reach magnitudes up to a few kilobars (Lambeck et al., 1984; McAdoo

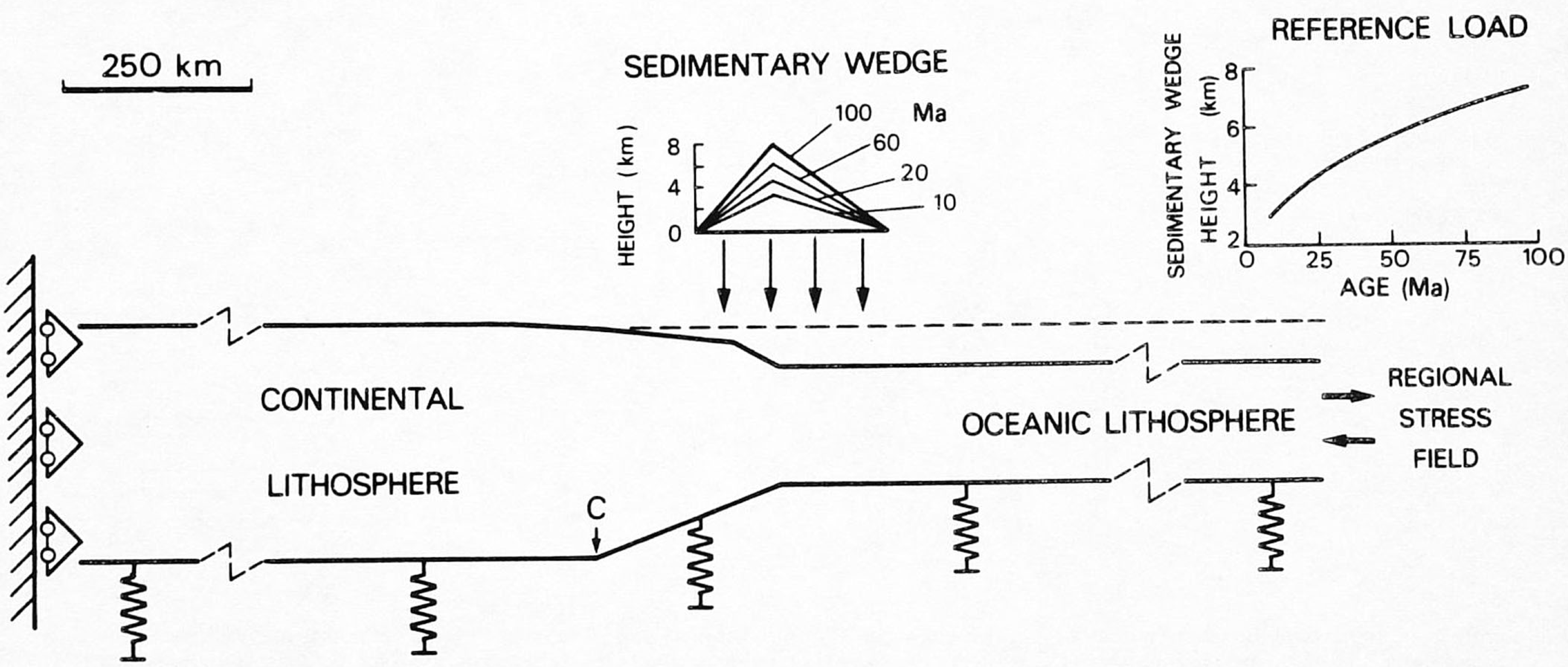


**Figure 1. Tectonic model for apparent sea-level fluctuations. Variations in intraplate stress field effect vertical displacements at a passive margin evolving through time due to thermal evolution of lithosphere and loading of lithosphere by wedge of sediments (see inset for reference model of sediment loading). Rheological differences between continental and oceanic lithosphere are omitted for simplicity.**

and Sandwell, 1985). Modeling of the stress field in the Indo-Australian plate (Cloetingh and Wortel, 1985) demonstrated that a stress level of several kilobars and the observed exceptionally high level of compressive deformation in the interior of the plate (McAdoo and Sandwell, 1985) are a transient feature unique to the present-day dynamics of the Indo-Australian plate.

Rapid fluctuations in stress fields are not limited to collision processes. Fragmentation of plates is also associated with drastic changes in stress state (Wortel and Cloetingh, 1981). Concentration of slab-pull forces dominates the plate-tectonic stress field (Wortel and Cloetingh, 1981; Patriat and Achache, 1984). Passive margins in plates that are not involved in collision or subduction processes are not subject to the influence of these slab-pull forces. In such circumstances, other sources of stress, e.g., membrane stresses (Turcotte and Oxburgh, 1976), can be much more important than the regional stress field induced by the remaining plate-tectonic forces. Thus, for passive margins located in the interiors of the American plates, stresses induced by sediment loading can be an order of magnitude greater than the regional stress field associated with ridge-push forces (Cloetingh and Wortel, 1985). The latter is typically an order of magnitude of a few hundred bars (Richardson et al., 1979). Under such circumstances, local adjustment of stresses at passive margins, e.g., by initiation of spreading in adjacent oceans, rarely involves changes of more than a few hundred bars. In the following section I investigate the effect of such changes in the stress field on the relative displacement of the lithosphere in sedimentary basins.

## APPARENT SEA-LEVEL CHANGES

The total deflection of the lithosphere at passive margins is dominated by sediment loading and thermal contraction (Sleep, 1971). Here we represent the sediment load by two adjacent triangular wedges, one on the continental shelf, the other on the continental rise. We adopt a reference model for sedimentary loading in which the maximum height of the sedimentary wedges corresponds to the thickness that would be attained provided that sedimentation has kept up with the subsidence predicted by the boundary layer model of the underlying oceanic lithosphere (Turcotte and Ahern, 1977). As a result, the maximum thickness of the sedimentary wedges increases gradually with the square root of the age up to a maximum value of 7.3 km at 100 Ma (Fig. 1). This reference model presents a fair representation of the sediment loading histories and thicknesses at passive margins and agrees with the observation that sediment accumulation rates tend to decrease with time after the initial rifting phase (Turcotte and Ahern, 1977).

Of interest here is the modification of the basin shape by variations in intraplate stress fields. Figure 2 (left) shows the effect for a sedimentary basin underlain by 30-m.y.-old oceanic lithosphere having a corresponding elastic plate thickness. A transition from a tension of 1 kbar to a compression of the same magnitude produces a net uplift (or apparent sea-level fall) of up to about 40 m at the edge of the basin. The deflections at other stress levels can be scaled in proportion to the magnitude of the applied horizontal stresses; a stress field of a few hundred bars corresponds to a deflection of about 10 m. The dependence of deflection on the age of the underlying lithosphere is demonstrated in Figure 2 (right). The differential uplift $\Delta w$, defined as the difference in deflection for the change in stress from tension to an equal magnitude compression is computed for the edge of the basin as a function of variations in the intraplate stress. Curves illustrate the deflections for changes from 2 to −2 kbar, from 1 to −1 kbar, from 0.5 to −0.5 kbar, and from 0.25 to −0.25 kbar, respectively, always with the same reference, time-dependent sediment load (negative stress denotes compression).

Similar changes in subsidence occur within the basins, although the relative subsidence here (on the order of a few hundred metres) is small in comparison with the total subsidence, which is on the order of several kilometres. The estimates of the magnitude of the vertical displacement inferred from our modeling of the deflection of a uniform elastic lithosphere are conservative. Introduction of a depth-dependent (Goetze and Evans, 1979) or viscoelastic rheology in the modeling, or adopting an effective elastic thickness of the continental lithosphere less than that of oceanic lithosphere, would enhance the effectiveness of the action of stress variations.

Figure 2 demonstrates that variations in relative sea level of at least 10 m can be caused by regional changes in the in-plane stresses on the order of a few hundred bars. If these stress reorganizations occur on a time scale of $10^6$ yr, then the associated rates of sea-level change are on the order of at least 1 cm/1000 yr. The actual magnitude obtained for a given change in stress is controlled by the magnitude of the perturbation or deflection of the lithosphere at the time that the in-plane stress is

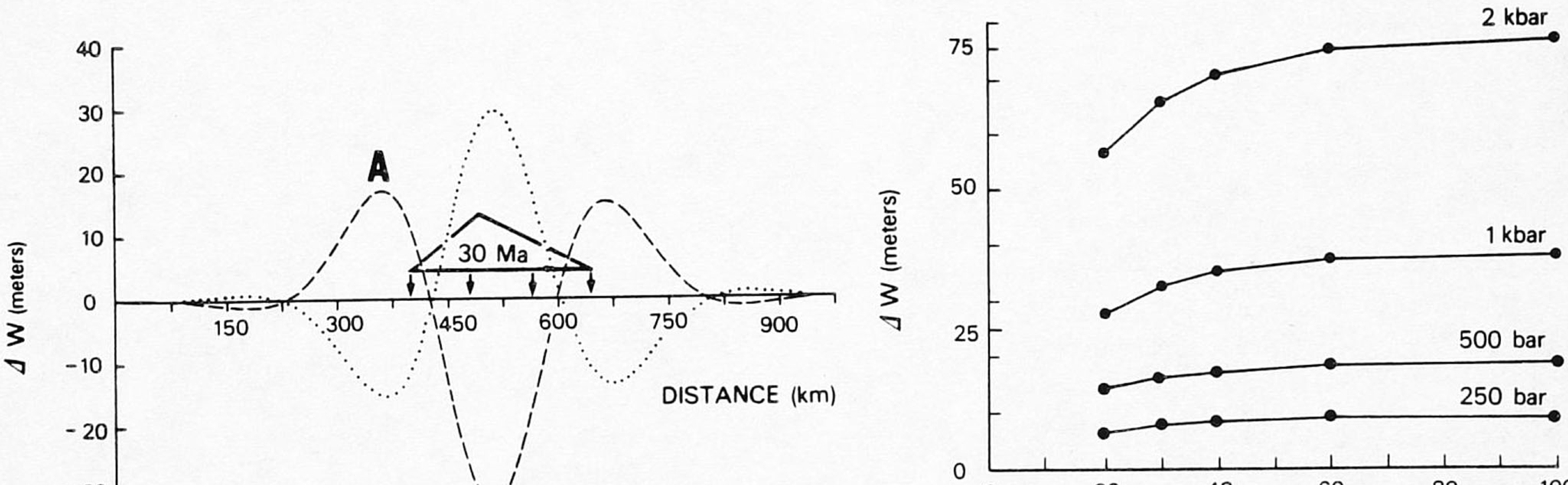


**Figure 2. Right: Differential uplift (in metres) at basin edge (position A in left plot) due to superposition of variations in intraplate stress field on flexure caused by sediment loading plotted as function of age of underlying lithosphere. Results are given for fixed stress transition from 2, 1, 0.5, and 0.25 kbar tension to 2, 1, 0.5, and 0.25 kbar compression, respectively. Left: Differential subsidence or uplift (in metres) from deflection due to sediment loading and thermal contraction of 30 Ma oceanic lithosphere, caused by intraplate stress field of 1 kbar compression (dashed curve) and tension (dotted curve). Uplift is positive (+), subsidence is negative (−).**

applied—that is, in the context of passive-margin evolution, on the rate of sedimentation and on the response of the lithosphere to this sediment load.

Although we have concentrated on the relation between tectonics and stratigraphy at passive margins, the tectonic mechanism discussed is applicable in a wider range of sedimentary environments. Other settings where lithosphere is flexed under the influence of sediment loading occur at foreland basins (Jordan, 1981). Despite its height of only a few hundred metres, the peripheral bulge flanking foreland basins is of particular stratigraphic interest (Jordan, 1981). The action of intraplate stresses of tensional or compressional character, of which the latter is more natural in this tectonic setting, can reduce or amplify the height of the peripheral bulge and, consequently, greatly influence the stratigraphic record at foreland basins.

## SEISMOSTRATIGRAPHIC RECORD: NEW SOURCE OF INFORMATION ON PALEO-STRESS

In the foregoing I have argued for a tectonic cause for apparent sea-level changes. Others (e.g., Bally, 1982; Watts, 1982; Veizer, 1985) have preceded me and my colleagues in this but were unable to identify a mechanism for lowerings in sea level. In particular, Bally (1982) has pointed out the existence of a strong correlation in timing of plate-tectonic reorganizations and lowerings in sea level shown in the Vail et al. (1977) curves. The Vail et al. (1977) global curve has been heavily weighted in favor of North America, the Gulf Coast, and the northern and central Atlantic margins. Therefore, the global cycles strongly reflect the seismostratigraphic record of basins in a tectonic setting dominated by rifting events in the northern and central Atlantic Ocean. This applies in particular to the North Sea Basin, where accurate timing of the different tectonic events is available (Ziegler, 1982). Adopting a magnitude of 50 m for the mid-Oligocene lowering in sea level, I have calibrated the Vail et al. (1977) generalized sea-level curve (see Fig. 3). On the basis of the outcome of the model calculations summarized in Figure 2 I have inverted the information on changes in sea level in the calibrated Vail et al. (1977) curve to derive a paleo-stress curve. The result is displayed in Figure 3; paleo-stresses are given relative to the present stress level. According to this modeling, falls in sea level are associated with relaxation of tensional intraplate stress or, equivalently, an increase in compressive stress (Fig. 3). As an example for comparison, Ziegler's (1982) timing of tectonic events in western Europe is given in Figure 3. Figure 3 shows

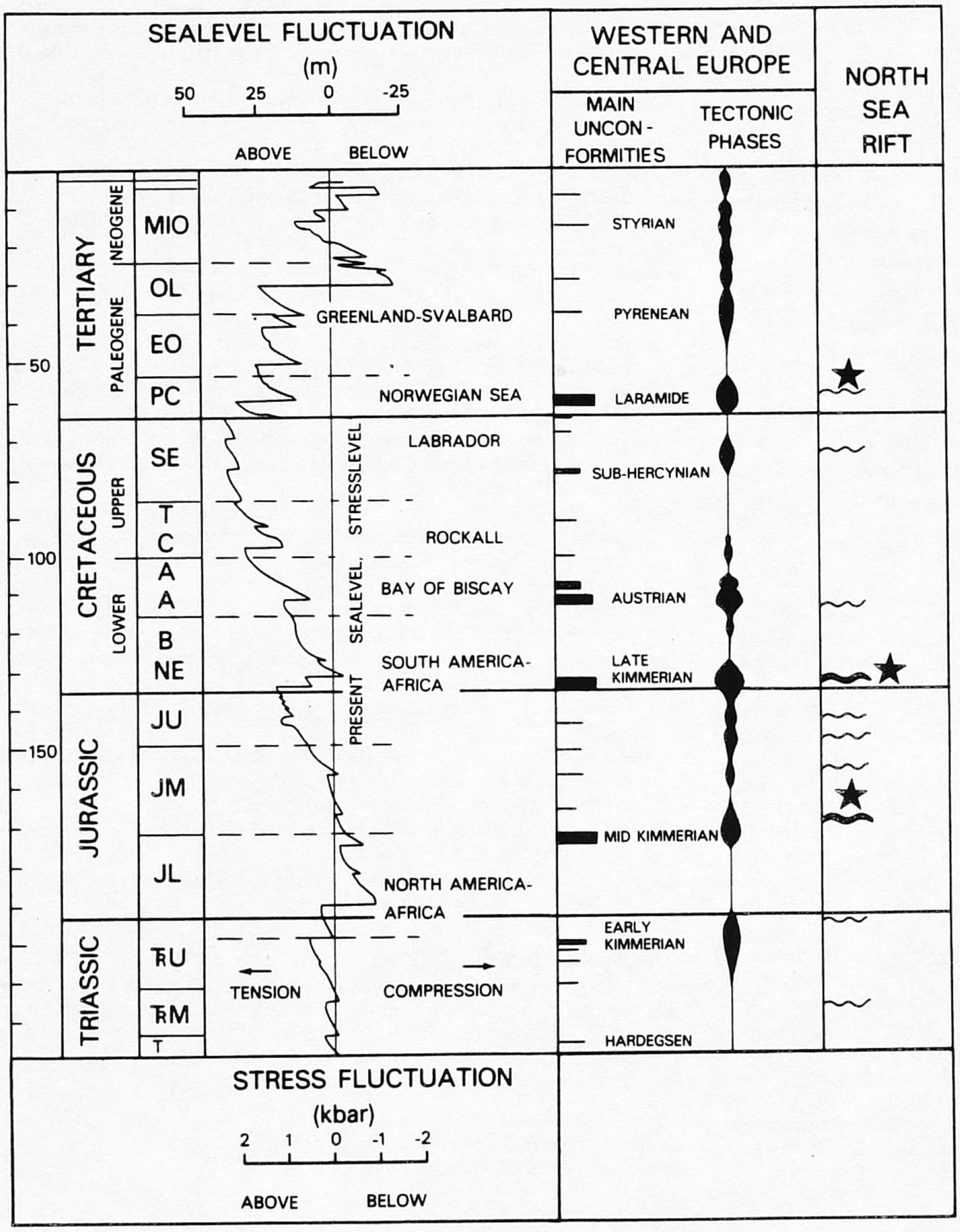


**Figure 3. Synthetic paleo-stress curve derived from generalized seismostratigraphic record (Vail et al., 1977). Columns on right side show timing of tectonic events (after Ziegler, 1982) in western Europe and North Sea basin, and are given for comparison. Also indicated are timings of onset of sea-floor spreading in Atlantic domain. Paleo-stresses are plotted relative to present-day stress level. Thin and heavy wavy lines denote minor and major rifting phases; stars denote volcanic activity.**

that the synthetic paleo-stress curve derived from the seismostratigraphic record mirrors the tectonic evolution of northwestern Europe and the North Sea Basin; rifting episodes correspond to relaxation of tensional paleo-stresses.

Relative changes in sea level documented for the eastern North American margin concomitant with the breakup of the eastern continental margin (Sheridan, 1983) and Early Cretaceous volcanism on the northeastern American margin (Jansa and Pe-Piper, 1985) are anticipated to be the reflection of adjustment of stress associated with these tectonic events. Other areas where the timing of tectonic events (and associated stress changes) correspond to lowerings in sea level include the south Pyrenean basin (Atkinson and Elliott, 1986), the Early Cretaceous foreland basins of western Montana (Suttner et al., 1986), the Cenozoic of the Mediterranean regin (Meulenkamp, 1982, and 1985, personal commun.), and the Australian passive margins (Cloetingh et al., 1985a). Here, changes from transgression to regression at the onset of the Banda arc and Himalayan collision events, associated with stress changes from tension to compression (Cloetingh and Wortel, 1985) have been noted.

In general, stress variations of a few hundred bars associated with local adjustment of stress at passive margins and intracratonic basins would suffice to explain the largest part of their seismostratigraphic record. Stress changes of more than 1 kbar are required in order to induce sea-level fluctuations with magnitudes on the order of 50 m such as those inferred for the mid-Oligocene event (Miller and Fairbanks, 1985; Watts and Thorne, 1984). These must be related to major reorganizations in lithospheric stress fields. In this context it is interesting to note that the mid-Oligocene fall in sea level is coincident with a global plate reorganization, presumably with a concomitant change in the paleo-stress state, in which the break up of the Farallon plate into the Cocos and Nazca plates (Wortel and Cloetingh, 1981) played a key role. The superposition of the effect of the tectonically induced fall in sea level and an important glacio-eustatic event might explain the exceptional magnitude (see also Schlanger and Premoli Silva, 1986) of the mid-Oligocene fall in sea level.

From the above, I conclude that the seismostratigraphic record could provide a new source of information for paleo-stress fields. Examination of the stratigraphic record of individual basins in a wide range of tectonic settings, in connection with independent numerical modeling of paleo-stresses (e.g., Wortel and Cloetingh, 1981) is required to fully exploit the potential of this new avenue of research.

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## ACKNOWLEDGMENTS


Kurt Lambeck and Herb McQueen made significant contributions to the initial phase of the work. Rinus Wortel, Julian Thorne, and Johan Meulenkamp offered valuable suggestions. I am grateful to Kevin Furlong and Norm Sleep for comments on an earlier version of this paper and to Seymour Schlanger for furnishing preprints of papers.

Manuscript received February 28, 1986
Manuscript accepted April 11, 1986