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INTRAPLATE STRESSES AND SEDIMENTARY BASIN EVOLUTION

Sierd Cloetingh[1], Henk Kooi[1], and Wim Groenewoud

Vening Meinesz Laboratory, University of Utrecht, The Netherlands

Abstract. Fluctuations in stress levels in the lithosphere can play an important role in basin stratigraphy and may provide a tectonic explanation for Vail's third order cycles in apparent sea levels. The gross onlap/offlap stratigraphic architecture of rifted basins can be described by models with changing horizontal stress fields. We demonstrate the effect of intraplate stress on vertical motions of the lithosphere for a depth-dependent rheology of the lithosphere with brittle fracture in its upper part and ductile flow in its lower part. Comparison of the outcome of the modeling with previous estimates by Cloetingh et al. [1985] of stress-induced subsidence and uplift based on an elastic plate model for the mechanical properties of the lithosphere demonstrates a considerable magnification of the induced vertical motions. These findings have important consequences for the stress levels required to explain the observed onlaps and offlaps at sedimentary basins. Similarly, they bear on our assessment of the relative importance of lithospheric dynamics versus glacio-eustasy as the controlling factor underlying sea-level cycles during periods with a non-icefree world. Modeling of the stratigraphy of the U.S. Atlantic margin demonstrates that the inferred transience in the horizontal stress field is qualitatively consistent with expectations based on what is known about plate kinematics during the same time period. The classic Mid-Oligocene unconformity can be explained by a compressional tectonic phase. The superposition of the stress effect associated with a major plate reorganization and a glacio-eustatic event might explain the exceptional magnitude of the Mid-Oligocene lowering of apparent sea level. Out-of-phase intrabasinal cycles such as relative uplift at the flanks and increased subsidence at the basin center, as observed for the Gulf de Lions margin, are predictable by the models. The large variations in estimates of magnitudes of short-term changes in relative sea level between various basins around the world are in agreement with predictions of the tectonic model.

Introduction

In recent years substantial progress has been made in quantitative modeling of sedimentary basins [e.g., Beaumont and Tankard, 1987]. Modeling studies have highlighted the important role of thermomechanical properties of the lithosphere in models of sedimentary basin evolution [e.g., Sleep, 1971; Watts et al., 1982; Beaumont et al., 1982]. Furthermore, they have quantified the contributions of a variety of lithospheric processes to the vertical motions of lithosphere at sedimentary basins. These processes include thermally induced contraction of the lithosphere amplified by the loading of sediments that accumulate in these basins [Sleep, 1971], isostatic response to crustal thinning and stretching [McKenzie, 1978] and flexural bending in response to vertical loading [Price, 1973; Beaumont, 1978].

Simultaneously, major advances have been made in the study of the stress fields in the plate interiors. Detailed analysis of earthquake focal mechanisms [Wiens and Stein, 1984; Bergman, 1986], in-situ stress measurements and analysis of break-out orientations obtained from wells [Bell and Gough, 1979; Zoback, 1985; Klein and Barr, 1986] have demonstrated the existence of consistently oriented present-day stress patterns in the lithosphere. Studies of paleo-stress fields within the plates by the application of analysis of microstructures [Letouzey, 1986; Bergerat, 1987; Philip, 1987] have expanded these findings by demonstrating temporal variations in the observed long-wavelength spatially coherent stress patterns. This work has provided strong evidence for the occurrence of large-scale rotations in the paleo-stress fields and also showed [see Philip, 1987] that the state of stress can vary enough to produce quite different deformations on relatively short time scales of approximately 5 Ma. At the same time, numerical modeling [Richardson et al., 1979; Wortel and Cloetingh, 1981, 1983; Cloetingh and Wortel, 1985, 1986] has yielded better understanding of the causes of the observed variations in stress levels and stress directions in the various lithospheric plates. These studies have demonstrated a causal relationship between the processes at plate boundaries and the deformation in the plate interiors [e.g., Johnson and Bally, 1986].

Most students of sedimentary basins agree that intraplate stresses play a crucial role during basin formation. The formation of sedimentary basins by lithospheric stretching, for example, requires tensional stress levels of the order of at least a few kbars [Cloetingh and Nieuwland, 1984; Houseman and England, 1986]. On the other hand, however, the effect of intraplate stresses on the subsequent evolution of sedimentary basins has been largely ignored in geodynamic modeling. However, recent work by Cloetingh et al. [1985], Cloetingh [1986] and Karner [1986] has demonstrated that temporal fluctuations in intraplate stress levels may have important consequences on basin stratigraphy and provide a tectonic explanation for short-term sea-level variations inferred from the stratigraphic record [Vail et al., 1977; Haq et al., 1987]. Vail and co-workers traditionally have interpreted their cyclic variations in onlap/offlap patterns in terms of a glacio-eustatic origin. This preference was primarily based on the inferred global change

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[1] Authors now at Department of Sedimentary Geology, Institute of Earth Sciences, Free University, P.O. Box 7161, 1007 MC Amsterdam, The Netherlands.

of the relative sea-level variations and the lack of a tectonic mechanism to explain Vail et al.'s third-order cycles. Although previous authors [e.g., Bally, 1982; Watts, 1982] have argued for a tectonic cause for apparent sea-level variations, they were unable to identify a tectonic mechanism operating on a time scale appropriate to explain the observed short-term changes of sea level [Pitman and Golovchenko, 1983]. A problem with the glacio-eustatic interpretation, however, is the lack of evidence in the geological and geochemical records for significant Mesozoic and Cenozoic glacial events prior to mid Tertiary time [Pitman and Golovchenko, 1983]. Hence, plate dynamics, and associated changes in stress levels in the plate's interiors offer a tectonic framework for quantitative dynamic stratigraphy.

Conversely, we have explored [Cloetingh, 1986; Lambeck et al., 1987] the use of the stratigraphic record as a new source of information on paleo-stress fields. These studies were carried out using a simplified elastic rheology for the lithosphere. Here we model the effect of intraplate stresses on lithospheric deflection for a more realistic depth-dependent rheology of the lithosphere [Goetze and Evans, 1979]. This modeling demonstrates that significantly lower stress levels are required to simulate the observed onlap and offlap patterns at the flanks of sedimentary basins. These findings bear on the scale of the underlying plate reorganizations versus a more local origin of the stress changes. More precise estimates of the magnitudes of the fluctuations in stress level are important for a quantitative assessment of the relative contributions of eustasy and stress-induced subsidence to the apparent sea-level record. Note that mechanisms for (thermally induced) long-term changes in sea level [e.g., Kominz, 1984; Heller and Angevine, 1985] fall beyond the scope of the present paper.

Intraplate Stresses and Elastic Deflection of the Lithosphere

In classical studies Smoluchowski [1909], Vening Meinesz [see Heiskanen and Vening Meinesz, 1958] and Gunn [1944] have investigated the flexural response of the lithosphere to applied horizontal forces. The flexural response of a uniform elastic lithosphere at a position x to an applied horizontal force F and a vertical load $q(x)$ is given by:

$$D\frac{d^4w}{dx^4} - F\frac{d^2w}{dx^2} + (\rho_m - \rho_i)gw = q(x)$$

where w is the displacement of the lithosphere, and D is the flexural rigidity ($D = E\,T^3 / 12\,(1-\nu^2)$), with E the Young's modulus, T the plate thickness, and ν the Poissons's ratio. The axial load F is equivalent to the product of the intraplate stress σ_N and the plate thickness T. ρ_m and ρ_i are respectively the densities of mantle material and the infill of the lithospheric depression, usually water or sediment, and g is the gravitational acceleration. The solution to this classical equation is easily obtained for some simple loading cases [e.g., Turcotte and Schubert, 1982].

Early studies showed that, in the absence of vertical loads, horizontal forces alone are quite inefficient at producing vertical deflections of the lithosphere. For compressional forces below the buckling limit the induced vertical deflections of the lithosphere are close to zero. These results and the lack of evidence for the existence of such horizontal forces, at that time, caused their possible effects to be ignored.

The situation is quite different in the presence of already existing vertical loads on the lithosphere. For example, in sedimentary basins constituting significant vertical loads, relatively low levels of intraplate stresses suffice to modulate the deflection, and hence the preexisting basin configuration [Cloetingh et al., 1985]. Crustal stretching or lithospheric flexure in response to vertical loading are, by their nature, inherently associated with such a preexisting deflection of the lithosphere.

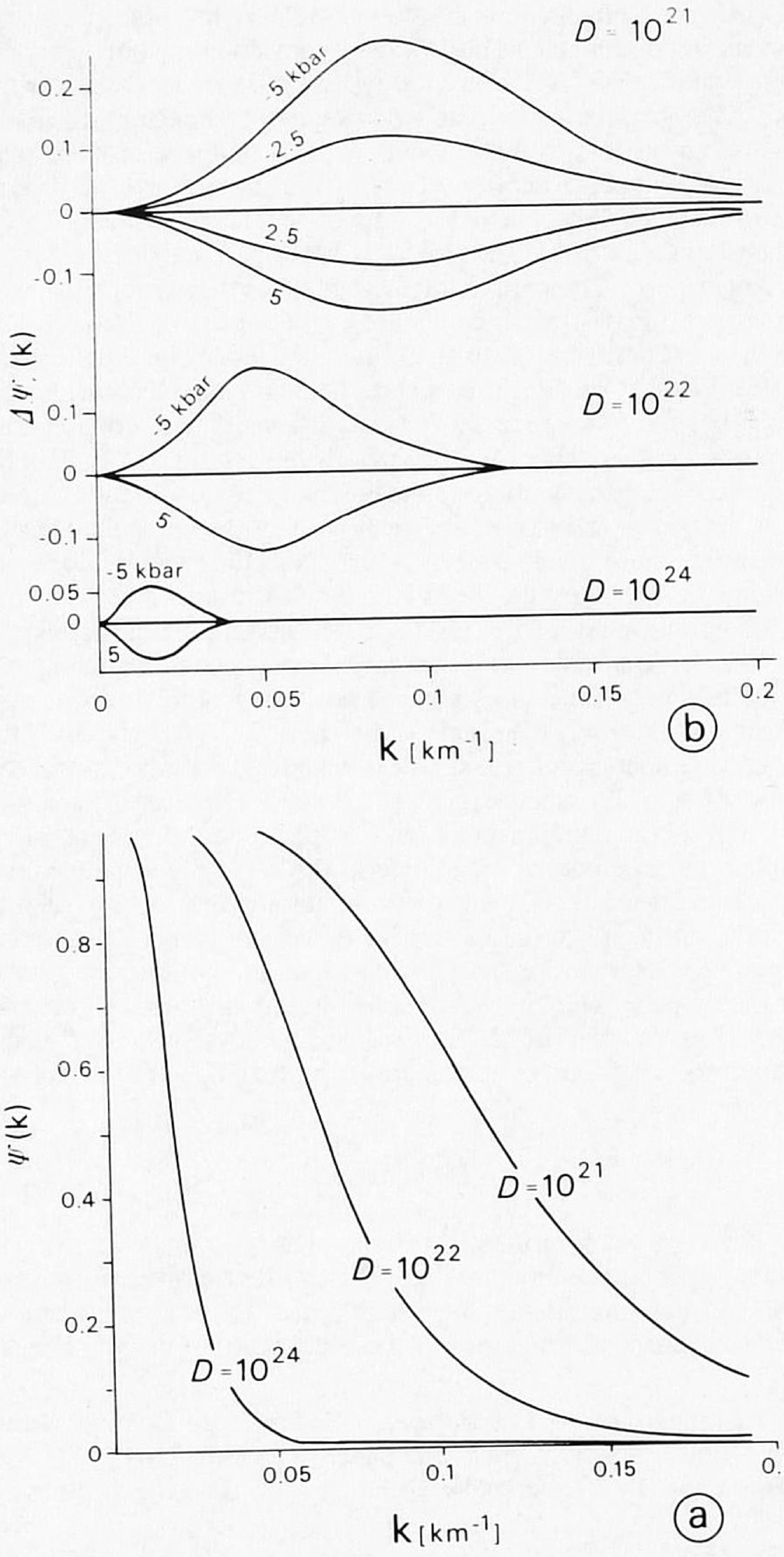

Fig. 1. *(a)* Flexural response functions $\Psi(k)$, in the absence of an intraplate stress field, for thin elastic plates with various flexural rigidities D in Nm, plotted as a function of wavenumber k. *(b)* The effect of intraplate stresses σ_N (tension is positive) on the response function. $\Delta\Psi_i(k) = \Psi_i(k) - \Psi(k)$, with $\Psi_i(k)$ the response function for an applied intraplate stress field. Results are given for the same flexural rigidities for various intraplate stresses σ_N in kbars. [After Stephenson and Lambeck, 1985].

Analytical solution. In analytical solutions of the equation describing the flexural behavior of thin elastic plates, the loading response of the plate is traditionally decomposed into its harmonic components by transforming the equation to the Fourier domain [Stephenson and Lambeck, 1985].

$$\Psi_i(k) = [1+\frac{D\,(2\pi k)^4-F\,(2\pi k)^2}{\rho_m g}]^{-1}$$

If $F=0$, then $\Psi_i(k) = \Psi(k)$, the flexural response function of the plate in the absence of intraplate stress. The wave number at which intraplate stresses most affect the flexural response of the lithosphere is almost completely determined by the plate's flexural rigidity [Stephenson and Lambeck, 1985]. These authors showed that the presence of intraplate stresses has a small but perceptible effect on this wave number, but exerts a controlling influence on the magnitude of the response for a given flexural rigidity. These features are illustrated in Figure 1, which shows the effect of intraplate stress fields of a magnitude of a few kbars on the flexural response of an elastic lithosphere.

Numerical solution. The analytic formulation of specific simplified problems, as given above, shows explicitly how the solution depends on various parameters. Numerical modeling techniques, however, have the advantage of allowing more realistic geometries and variations in parameters to be handled, adding flexibility to the analysis. Cloetingh et al. [1985] considered the case of an elastic lithosphere evolving through time in response to changing thermal condition and loading with a wedge of sediments [Turcotte and Ahern, 1977]. They showed that vertical deflections of the lithosphere of up to a hundred meters may be induced by the action of lithospheric stress fields with a magnitude of up to a few kbars (Figure 2). When horizontal compression occurs, the peripheral bulge flanking the basin is magnified, while simultaneously migrating in a seaward direction, such that the basin flanks are uplifted. As a result an offlap develops, and an apparent fall in sea level results, which may expose the sediments and produce an unconformity. Simultaneously, the basin center undergoes deepening (Figure 2b), resulting in a steeper basin slope. For a horizontal tensional intraplate stress field, the flanks of the basin subside such that the shoreline migrates landward, producing an apparent rise in sea level, so that renewed deposition, with a corresponding facies change, is possible. In this case the center of the basin is shallowed (Figure 2b), and the basin slope is reduced.

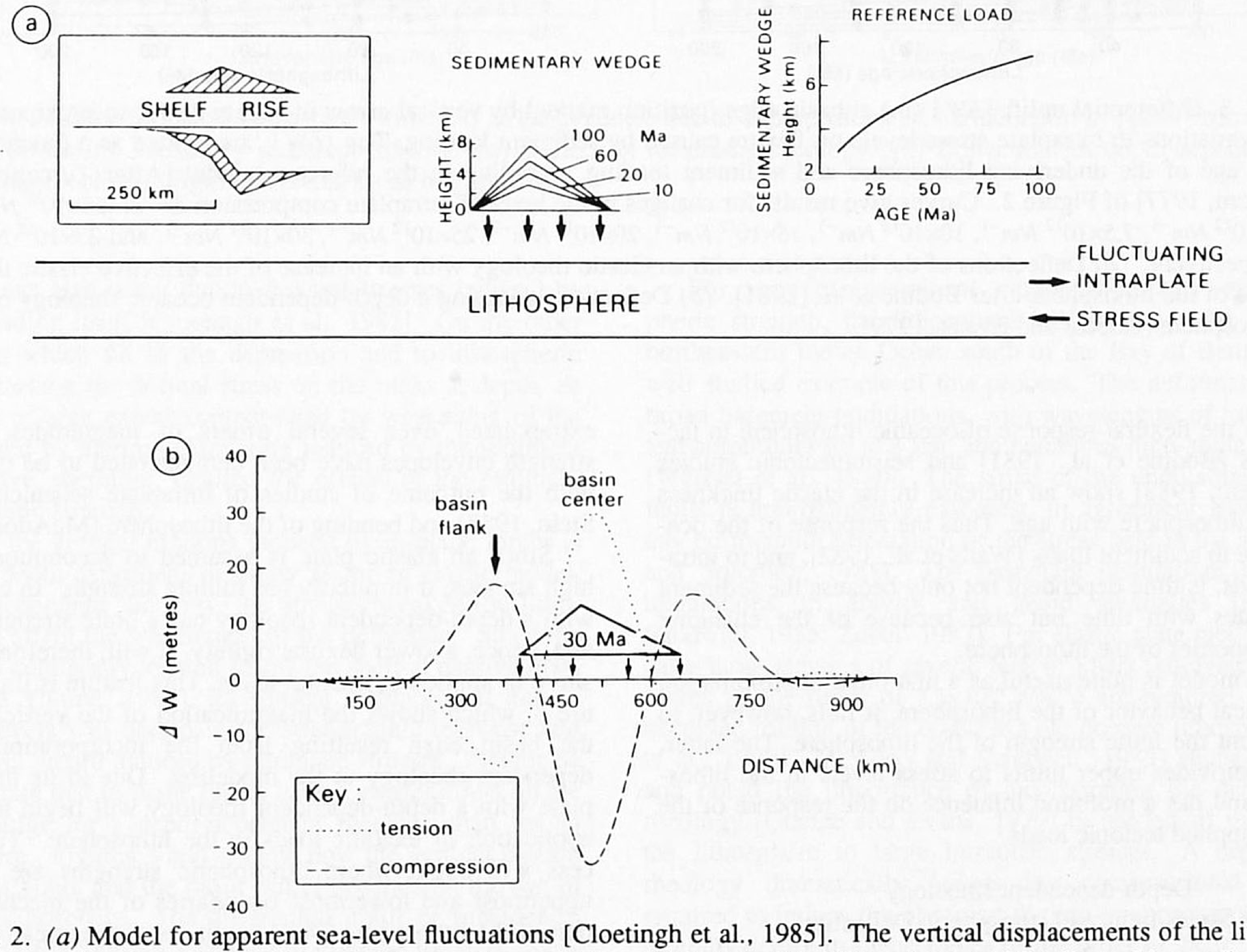

Fig. 2. *(a)* Model for apparent sea-level fluctuations [Cloetingh et al., 1985]. The vertical displacements of the lithosphere evolve through time because of thermal contraction, stiffening of the lithosphere, and loading with a sediment wedge. Inset shows position of this wedge on the outer shelf,slope and rise of a passive margin. Sedimentation is assumed to be sufficiently rapid to equal approximately the subsidence rate [Turcotte and Ahern, 1977]. *(b)* Effect of variations in intraplate stress fields on the deflection of 30 Ma old oceanic lithosphere. Differential subsidence or uplift (meters) relative to the deflection in the absence of an intraplate stress field is given for intraplate stress fields of 1 kbar compression (an in-plane force of $-2.17\times10^{12}\ Nm^{-1}$ (dashed)), and 1 kbar tension, (an in-plane force of $2.17\times10^{12}\ Nm^{-1}$ (dotted)). Sign convention: uplift is positive, subsidence is negative. Note the opposite effects at the flanks of the basin and at the basin center. [After Cloetingh et al., 1985].

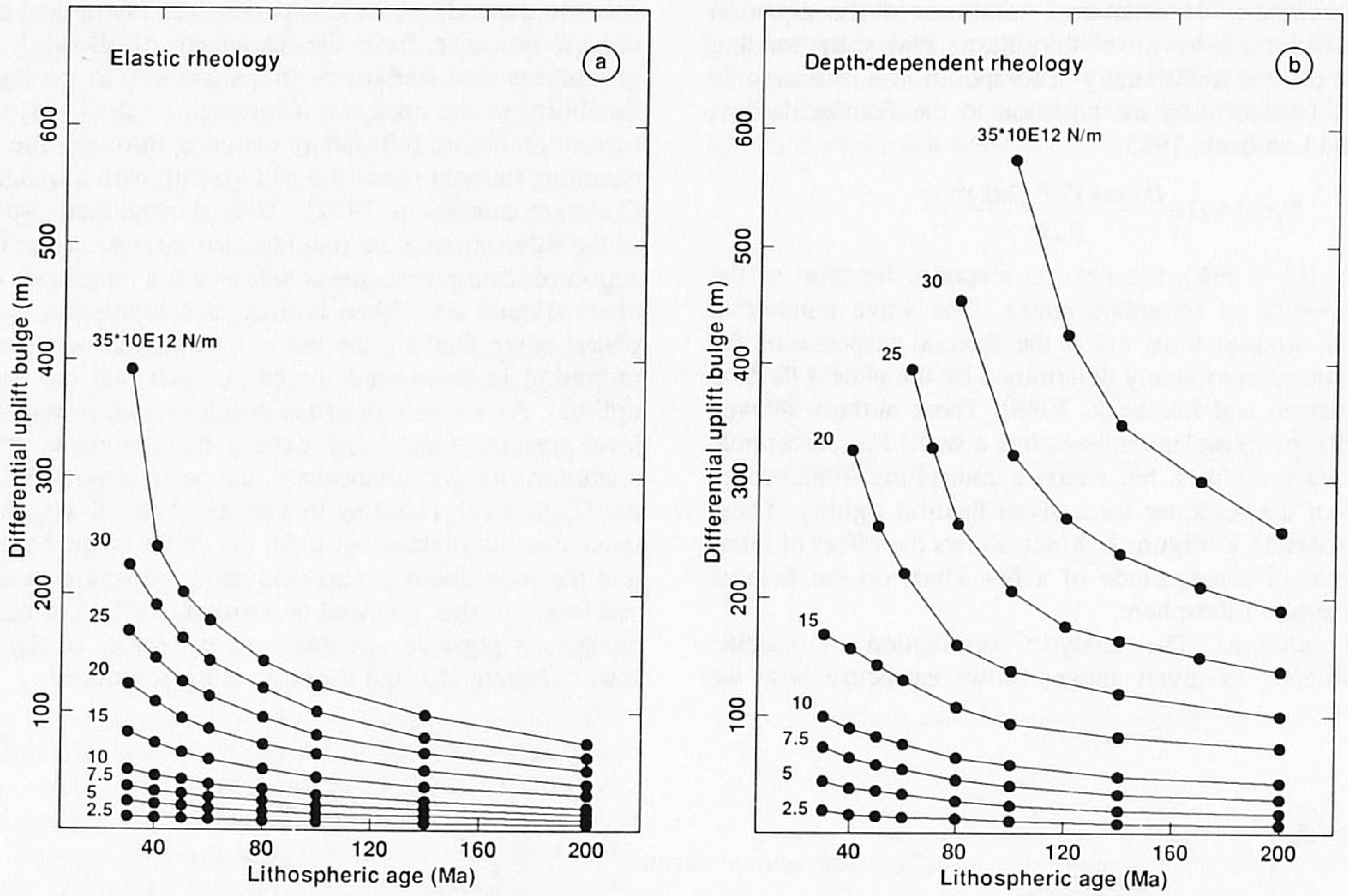

Fig. 3. Differential uplift $|\Delta W|$ (m) at basin edge (position marked by vertical arrow in Figure 2) due to superposition of variations in intraplate stress levels on flexure caused by sediment loading. The $|\Delta W|$ are plotted as a function of the age of the underlying lithosphere and sediment loading according to the reference model [After Turcotte and Ahern, 1977] of Figure 2. Curves give results for changes in the level of intraplate compression ΔF of $2.5\times10^{12}\ Nm^{-1}$, $5\times10^{12}\ Nm^{-1}$, $7.5\times10^{12}\ Nm^{-1}$, $10\times10^{12}\ Nm^{-1}$, $15\times10^{12}\ Nm^{-1}$, $20\times10^{12}\ Nm^{-1}$, $25\times10^{12}\ Nm^{-1}$, $30\times10^{12}\ Nm^{-1}$, and $35\times10^{12}\ Nm^{-1}$, respectively. *(a)* Deflections of the lithosphere with an elastic rheology with an increase of the effective elastic thickness of the lithosphere after Bodine et al. [1981]. *(b)* Deflections adopting a depth-dependent oceanic rheology of the lithosphere [Goetze and Evans, 1979].

Analysis of the flexural response of oceanic lithosphere to tectonic processes [Bodine et al., 1981] and seismotectonic studies [Wiens and Stein, 1983] show an increase in the elastic thickness of the oceanic lithosphere with age. Thus the response of the oceanic lithosphere to sediment loads [Watts et al., 1982], and to intraplate stress fields, is time dependent not only because the sediment load accumulates with time but also because of the changing mechanical properties of the lithosphere.

The elastic model is quite useful as a first order approximation of the mechanical behavior of the lithosphere. It fails, however, to take into account the finite strength of the lithosphere. The latter, by its nature, provides upper limits to stress levels in the lithospheric plates, and has a profound influence on the response of the lithosphere to applied tectonic loads.

Depth-dependent Rheology and Stress-induced Lithospheric Deflection

A more realistic model of the mechanical properties of the lithosphere is based on the extrapolation of rock-mechanics data from laboratory experiments to geological conditions [Goetze and Evans, 1979]. These workers developed a depth-dependent rheology of the lithosphere combining Byerlee's law [Byerlee, 1978] in the brittle domain with temperature-dependent constitutive equations describing the deformation in the ductile regime. Although extrapolated over several orders of magnitudes, the resulting strength envelopes have been demonstrated to be quite consistent with the outcome of studies of intraplate seismicity [Wiens and Stein, 1983] and bending of the lithosphere [McAdoo et al., 1985].

Since an elastic plate is assumed to accommodate arbitrarily high stresses, it implicitly has infinite strength. In contrast, a plate with a depth-dependent rheology has a finite strength at any depth and, hence, a lower flexural rigidity. It will, therefore, be more sensitive to applied horizontal loads. This feature is illustrated in Figure 3, which shows the magnification of the vertical deflection at the basin edge resulting from the incorporation of a depth-dependent rheology in the modeling. Due to its finite strength, a plate with a depth-dependent rheology will begin to fail upon the application of tectonic loads in the lithosphere. This failure process will begin where lithospheric strengths are lowest, at the uppermost and lowermost boundaries of the mechanically strong part of the lithosphere. As a result, the mechanically strong part of the lithosphere will be thinned to a level which ultimately depends on the ratio of the integrated strength of the lithosphere to the applied stress. This results in a reduction of the flexural wavelength of the plate when a tectonic load is applied. This effect applies to both compressional and tensional stresses, and adds a complexity not present in the case of an elastic rheology, where compression and tension have an opposite effect on the flexural shape of the basin (Figure 2b). Rheological weakening of

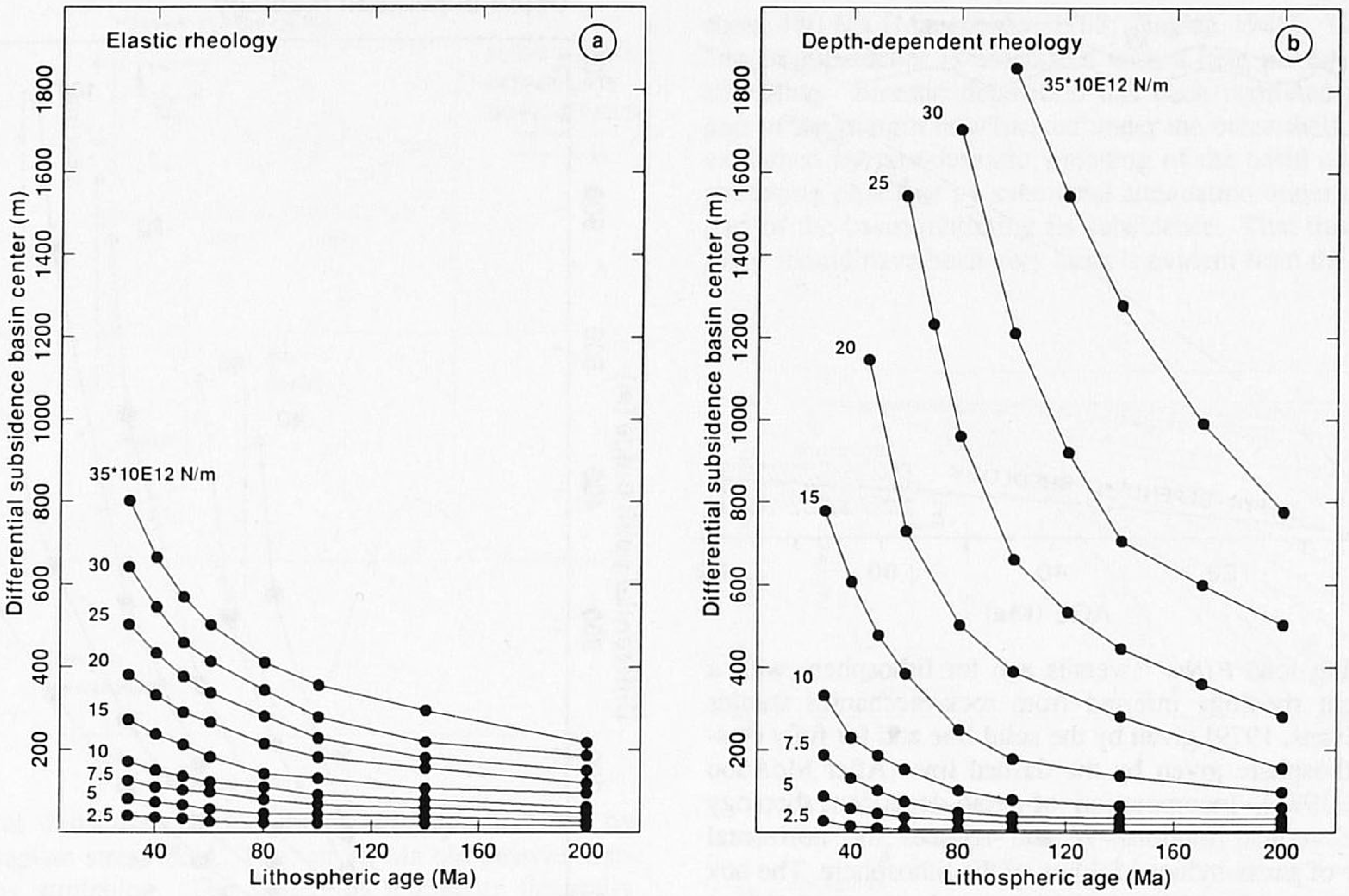

Fig. 4. Differential subsidence $|\Delta W|$ (meters) at basin center due to superposition of variations in in-plane compression on flexure caused by sediment loading. *(a)* Deflection for elastic rheology. *(b)* Deflection for depth-dependent oceanic rheology. Figure conventions as in Figure 3.

the lithosphere can also occur due to flexural stresses induced by the sediment loading itself [Cloetingh et al., 1982]. On the other hand, sediments which fill in the depression add to lithospheric strength by increasing the normal stress on the rocks at depth, an effect that is to a large extent compensated by weakening of the lithosphere caused by thermal blanketing induced by the sediment loading. We have, therefore, ignored the effects of the sediment load on lithospheric strength.

The sign of the vertical motions induced by in-plane forces is the same for a depth-dependent rheology as for an elastic model. For the depth-dependent rheology, the stresses weaken the lithosphere and thus affect the wavelength of the deflection. Since the flexural bulge is commonly located below the shelf at passive margins [Watts and Thorne, 1984], its vertical displacement due to varying stress levels will dominate the stratigraphic response and apparent sea-level record induced by intraplate stresses. Figures 3a and 3b demonstrate that in-plane forces have a greater effect on the height of the bulge for a depth-dependent rheology than for an elastic lithosphere. Figures 3 and 4 show how the vertical motion of the peripheral bulge and the basin center depends on the age of the underlying lithosphere. The differential uplift or subsidence, the difference in deflection for a change in in-plane force, is calculated for the basin flank (Figure 3) and center (Figure 4) as a function of in-plane force. Figures 3 and 4 show, that compared to the elastic plate model, a depth-dependent rheology of the lithosphere substantially enhances the ability of intraplate stresses to induce vertical deflections at the basin edge. Due to the age-dependence of the lithospheric strength, the magnification is particularly pronounced for young lithosphere.

For large compressional intraplate stresses, close to lithospheric strength, the lithosphere will buckle. The region in the northeastern Indian Ocean south of the Bay of Bengal provides a well studied example of this process. The deformation occurs by broad basement undulations, with wavelengths of roughly 200 km and amplitudes up to 3 km, and numerous high-angle reverse faults [Weissel et al., 1980]. The strike of the undulations and reverse faults is approximately east-west, in agreement with the present-day north-south orientation of the stress field in the area [Bergman and Solomon, 1985]. The basement undulations coincide with undulations in gravity and geoid anomalies [McAdoo and Sandwell, 1985; Zuber, 1987]. For elastic plate models, unrealistically large stresses of several tens of kbars (equivalent to in-plane forces of the order of 2.5×10^{14} Nm^{-1}) are required to induce the observed folding of the 60-80 Ma old oceanic lithosphere [Weissel et al., 1980]. McAdoo and Sandwell [1985] studied this folding and noted the importance of incorporating the depth-dependent rheology [Goetze and Evans, 1979] in models of the response of the lithosphere to large intraplate stresses. A depth-dependent rheology dramatically lowers the compressional stress level required to induce the observed folding to approximately 5-6 kbar, or equivalently in-plane forces of the order of 2×10^{13} Nm^{-1} (Figure 5). This figure shows that McAdoo and Sandwell's [1985] results are in excellent agreement with estimates from numerical modeling of intraplate stresses [Cloetingh and Wortel, 1985, 1986; see Figure 5]. In these models the exceptionally high level of the intraplate stresses in the northeastern Indian Ocean results from the special dynamic situation of the present Indian plate. The calculated stresses depend on the plate geometry and the boundary

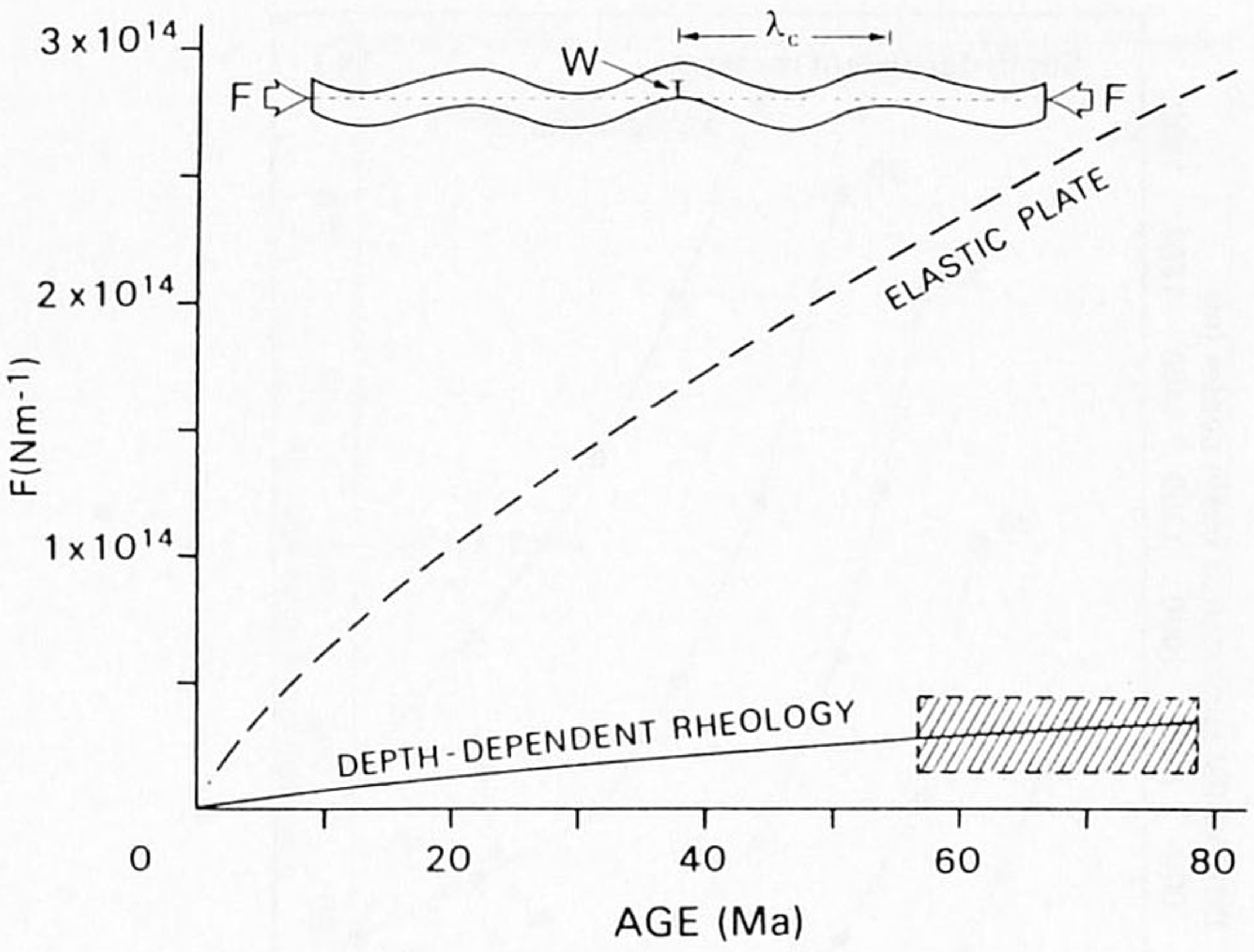

Fig. 5. Buckling load $F\,(Nm^{-1})$ versus age for lithosphere with a depth-dependent rheology inferred from rock-mechanics studies [Goetze and Evans, 1979] given by the solid line and for fully elastic oceanic lithosphere given by the dashed line [After McAdoo and Sandwell, 1985]. Incorporation of depth-dependent rheology magnifies the vertical motions W and reduces the horizontal wavelength λ_c of stress-induced folding of the lithosphere. The box indicates stress levels calculated for the area in the northeastern Indian Ocean [Cloetingh and Wortel, 1985] where folding of oceanic lithosphere under the influence of compressional stresses has been observed [McAdoo and Sandwell, 1985].

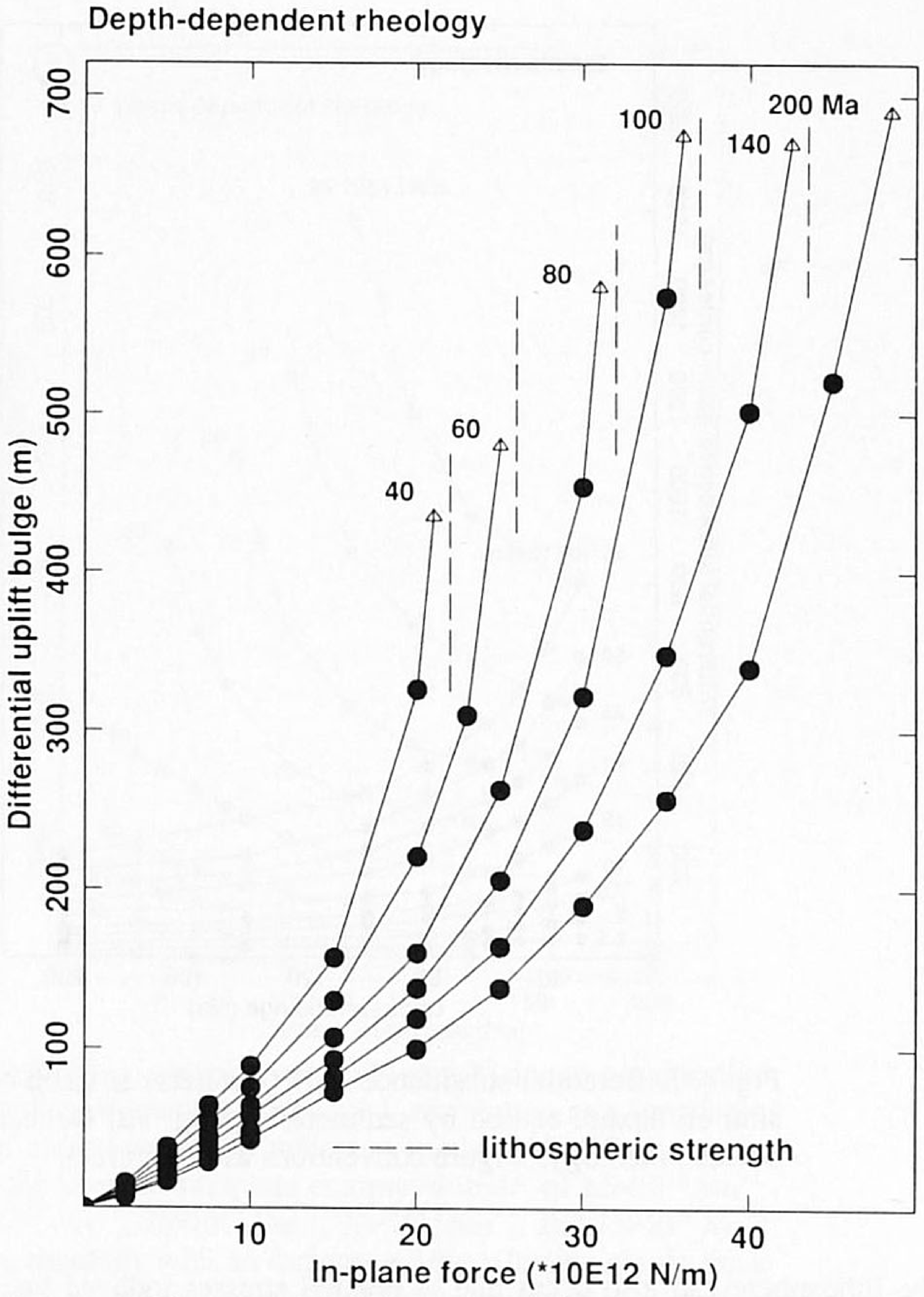

Fig. 6. Uplift of the lithosphere $|\Delta W|$ (km) at the position of the flexural bulge flanking the basin induced by in-plane compressional forces up to the lithospheric strength for various lithospheric ages. Curves have been calculated for an oceanic depth-dependent lithospheric rheology. The dashed vertical lines indicate the strength of lithosphere in compression for ages of 40, 60, 80, 100, 140 and 200 Ma. Arrows indicate the transition to displacements of the lithosphere reaching magnitudes of several kilometers, which occurs when in-plane compression approaches the integrated strength of the lithosphere.

forces applied, which are assumed to vary with the age of the subducted lithosphere. In this case, the large age contrasts, the Himalayan collision and the specific geometry of the plate give rise to high stresses. In plates not involved in continental collision, rifting, or plate reorganizations, stresses will, in general be lower, with values as low as a few hundred bars (equivalent to in-plane force of the order of $2{\times}10^{12}\ Nm^{-1}$) calculated for the present Nazca plate [Wortel and Cloetingh, 1983].

Syn-depositional folding of oceanic lithosphere might have some interesting analogues in the continents [e.g., Hoffman et al., 1988; van Wamel, 1987]. Rheological models indicate that continental lithosphere can be substantially weaker than oceanic lithosphere [Kirby, 1985; Carter and Tsen, 1987]. This primarily reflects mineralogic differences between oceanic and continental lithosphere and is thought to have a profound influence on the nature of the rifting [Vink et al., 1984; Steckler and Ten Brink, 1986; Shudofsky et al., 1987]. Similarly, we expect that a given change in intraplate stress will induce larger vertical motions in continental lithosphere than in oceanic lithosphere, with important implications for vertical motions at intracratonic and foreland basins.

Lithospheric folding will occur only if high compressional stress levels are induced in the lithosphere, by special dynamic situations, such as collision processes like those presently occurring between the Indian and Eurasian plates. Figure 6 shows the transition between vertical motions of the order of a hundred meters, which are reflected in the apparent sea-level record, and the more dramatic vertical motions with magnitudes of the order of a few kilometers which result from the accumulation of stress to levels close to the strength of the lithosphere.

Intraplate Stress and Basin Stratigraphy

Figure 7 schematically illustrates the relative movement between sea level and the lithosphere at the flank of a flexural basin immediately landward of the principal sediment load predicted by numerical calculations [Cloetingh et al., 1985] using the elastic plate model. The synthetic stratigraphy at the basin edge is schematically shown for three situations. In one, long-term flexural widening of the basin results from cooling [Watts, 1982] in the absence of an intraplate stress field (Figure 8a). Figures 8b and 8c show the same situation with a superimposed transition to 500 bar compression (Figure 8b) or tension (Figure 8c) at 50 Ma. As noted by Watts [1982], the thermally induced flexural widening of the basin (Figure 8a) provides an adequate explanation for long-term phases of coastal onlap. However by its long-term nature, it fails to produce the punctuated character of the stratigraphy of sedimentary basins. Figures 8b,c demonstrate that the incorporation

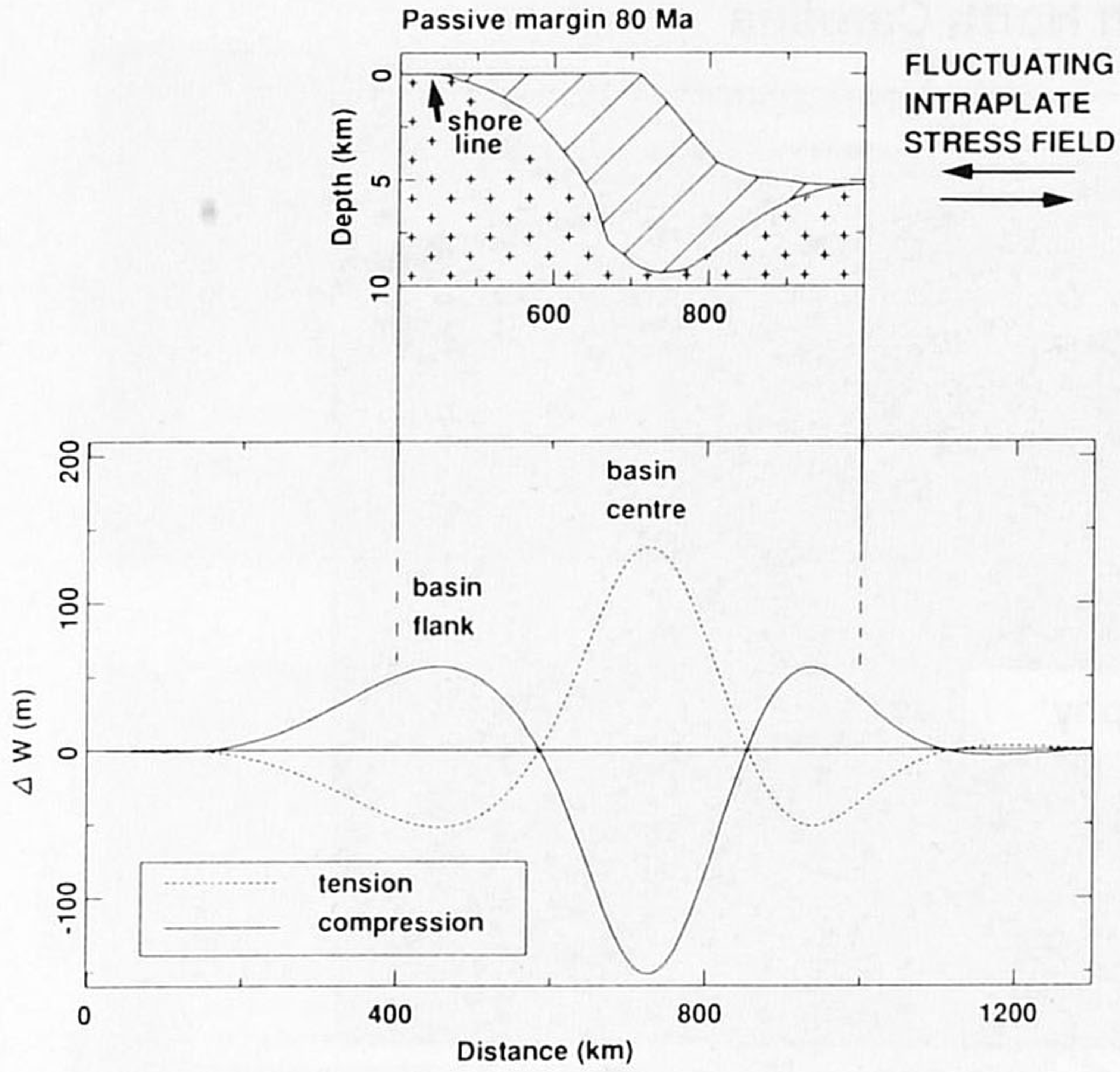

Fig. 7. Flexural deflections at a sedimentary basin induced by changes in intraplate stress field. Top: an 80 Ma old passive margin initiated by stretching. The wedge of sediments flexurally loads an elastic plate. The thickness of the plate varies horizontally due to lateral changes in the temperature structure of the lithosphere. Bottom: Differential subsidence or uplift (meters) induced by a change to 1 kbar compression (solid line) and 1 kbar tension (dashed line).

of intraplate stresses in elastic models of basin evolution can in principle predict a succession of alternating rapid onlaps and offlaps observed along the flanks of basins such as the U.S. Atlantic margin [Sleep and Snell, 1976; Figure 9]. We use the U.S. Atlantic margin for a numerical simulation of the stratigraphy for several reasons. The margin stratigraphy has been extensively documented [e.g., Poag and Schlee, 1984] and has previously been the subject of detailed quantitative modeling [Sleep and Snell, 1976; Watts and Thorne, 1984; Steckler et al., 1988]. Sleep and Snell [1976] proposed a visco-elastic model of the lithosphere to account for the observed late-stage narrowing of the North-Carolina margin. Watts and Thorne [1984] and Steckler et al. [1988] employed a two-layer stretching model adopting an elastic rheology of the lithosphere and zero intraplate stresses. They assumed eustatic long-term and short-term sea-level fluctuations throughout the basin evolution. Our modeling approach resembles the one taken by Watts and Thorne [1984] and Steckler et al. [1988] in adopting a two-layer stretching model for basin initiation but also incorporates the effects of finite and multiple stretching phases and intraplate stresses in the stratigraphic modeling. We use a finite-difference approach for the thermal calculations [Verwer, 1977].

Although of limited impact for the late-stage development of the basin, the incorporation of finite stretching rates severely affects syn-rift and early post-rift subsidence and sedimentation [Jarvis and McKenzie, 1980; Cochran, 1983]. There is general agreement that the initial rifting phase began in the Late Carnian (approximately 225 Ma), whereas sea floor spreading began at about 180 Ma [Manspeizer, 1985; Ziegler, 1988]. Thus the initiation of subsidence is associated with a long period of rifting and stretching. Jurassic deposition has been restricted to the deeper part of the margin now located under the outer shelf. This may be explained by post-Jurassic widening of the basin due to a second stretching phase, or by subcrustal attenuation under the inner shelf part of the basin inhibiting its subsidence. That this thermal anomaly should have been very large is evident from the long duration

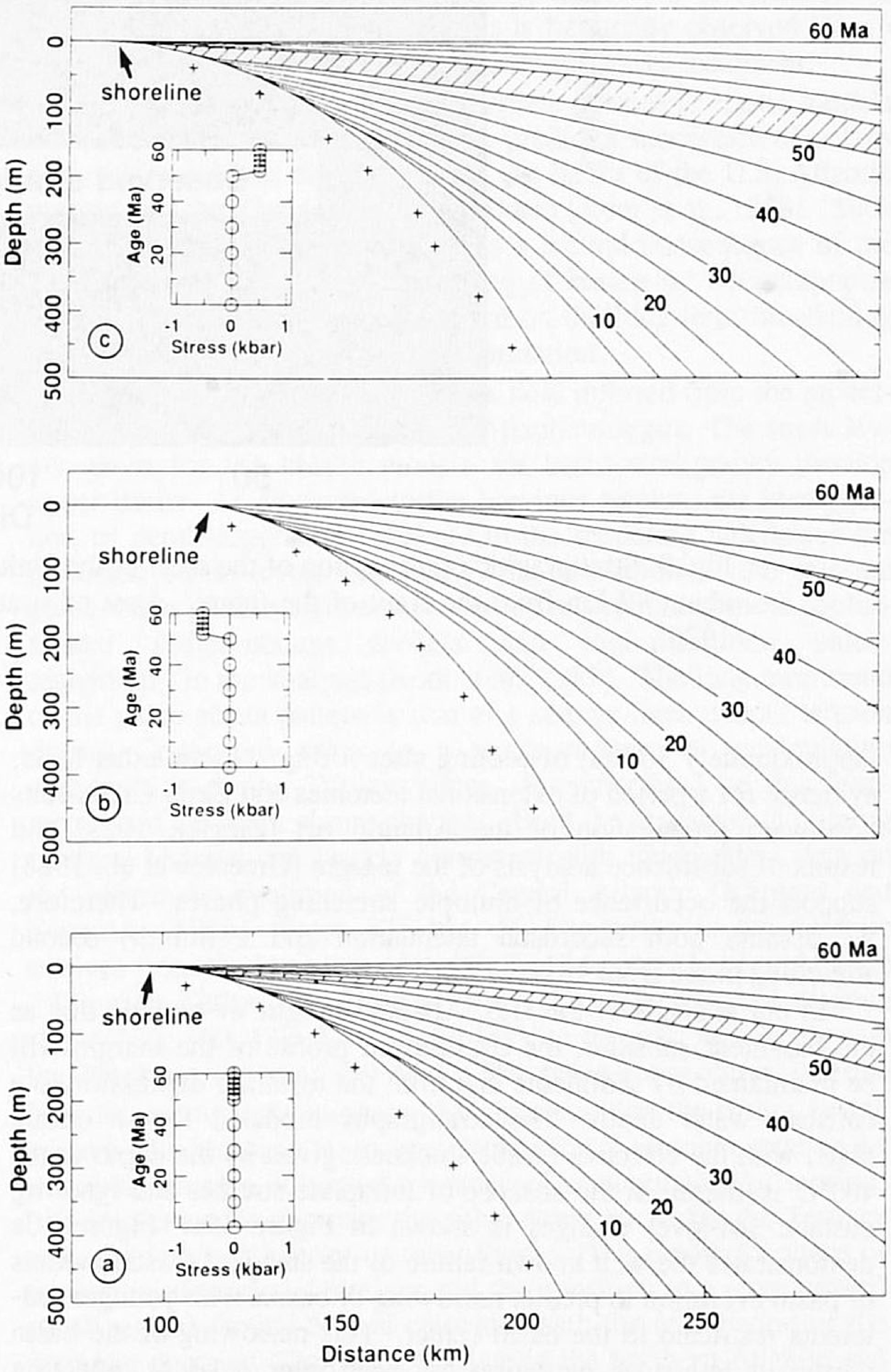

Fig. 8. Synthetic stratigraphy for a 60 Ma old passive margin, that was initiated by lithospheric stretching followed by thermal subsidence and flexural infilling of the resulting depression. Hachuring indicates the position of a sedimentary package bounded by isochrons of 50 Ma and 52 Ma after basin formation. *(a)* Continuous onlap associated with long-term cooling of the lithosphere in the absence of intraplate stress fields. *(b)* A transition to 500 bar in-plane compression at 50 Ma induces uplift of the peripheral bulge, narrowing of the basin and a phase of rapid offlap, which is followed by a long-term phase of gradual onlap due to thermal subsidence. *(c)* A transition to 500 bar in-plane tension at 50 Ma induces downwarp of the peripheral bulge, widening of the basin and a phase of rapid basement onlap.

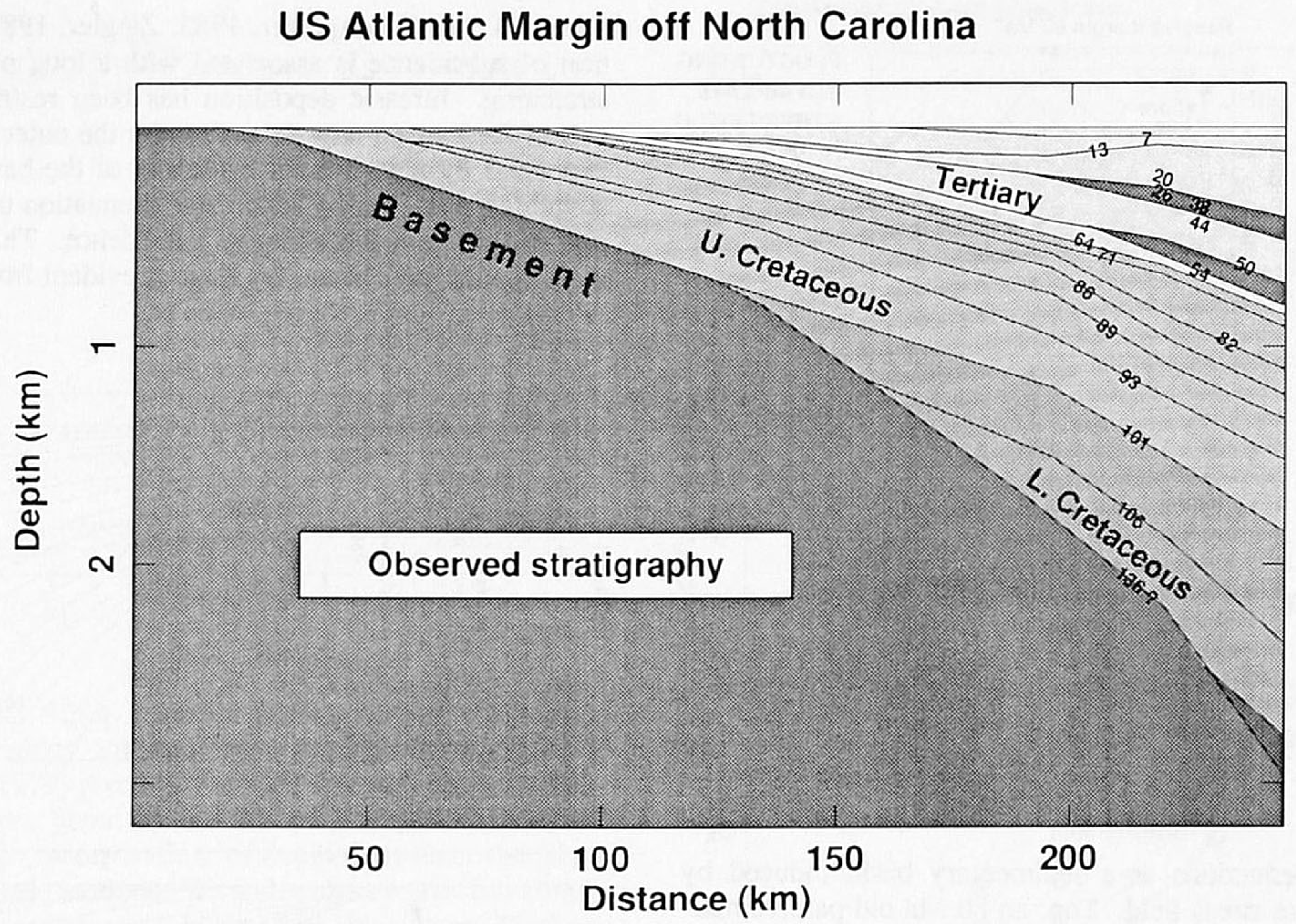

Fig. 9. Stratigraphic cross section of the shelf of the United States Atlantic margin at Cape Hatteras. The shelf break is about 40 km from the right of the figure. Ages of stratigraphic boundaries are given in Ma [After Sleep and Snell, 1976].

(approximately 36 Ma) of cooling after rifting. On the other hand, evidence for a period of extensional tectonics and Early Cretaceous northward propagation of the Atlantic rift [Ziegler, 1988] and results of subsidence analysis of the margin [Greenlee et al., 1988] support the occurrence of multiple stretching phases. Therefore, we assume both subcrustal attenuation and a (minor) second stretching phase from 131-119 Ma.

In our analysis of the U.S. Atlantic margin we assume that as the basement subsides, the equilibrium profile of the margin will be maintained by sediments that infill the resulting depression to a constant water depth. The stratigraphy modeled for an elastic plate, with the effective elastic thickness given by the depth to the $400^o C$ isotherm, in the absence of intraplate stresses and ignoring eustatic sea-level changes is shown in Figure 10a. Figure 10a demonstrates the well known failure of the standard elastic models of basin evolution to predict narrowing of basins with younger sediments restricted to the basin center. This narrowing of the basin during its late-stage evolution has been interpreted as reflecting either the response of the basin to a phase of visco-elastic relaxation [Sleep and Snell, 1976], or to a long-term eustatic sea-level fall [Watts and Thorne, 1984]. The total thickness of the Cenozoic sediments provides an independent constraint for the magnitude of the proposed long-term lowering in sea level. Our modeling yields an upper estimate of approximately 100 meters for the long-term post-Late Cretaceous fall in sea level. We therefore incorporated a long-term sea-level curve with a highstand of 100 meters during the end of the Cretaceous, a curve equivalent to the minimum curve by Kominz [1984]. The resulting stratigraphic model (Figure 10b) demonstrates that although the incorporation of long-term changes in sea level enhances the Cenozoic narrowing of the margin, a long-term post-Late Cretaceous decline in sea level alone cannot cause both the documented basin narrowing and the total thickness of sediments accumulated during this time. We propose that much of the observed non-depositional or erosional character of the shelf surface is caused by stress-induced uplift of the basin flank. Similarly, short-term changes in intraplate stress levels can produce the Early Eocene and Oligocene onlap/offlap phases. Figure 10c shows the best fit to the observed stratigraphy for a two-layered stretching model and an elastic rheology, incorporating long-term sea level changes after Kominz [1984] and a fluctuating intraplate stress level in the stratigraphic modeling. It appears that the margin stratigraphy can be simulated by relaxation of overall tensional Mesozoic intraplate stress fields and a transition to compressional stress, whose level increases with time during the Tertiary.

During rifting phases, eventually followed by continental break-up, the tensional stresses will be reduced. Rifting in the Southern Atlantic, for example, rather than instantaneously, occurred as discrete rifting phases, with stepwise relaxation of tensional stresses. This process might explain the enigmatic high-frequency sea-level fluctuations in Cretaceous times that do not correlate with accelerations in plate spreading or increases in ridge lengths [Schlanger, 1986]. Similarly, the correlation of short-term sea-level fluctuations at both sides of the Atlantic may reflect rifting-related accumulation and relaxation of tensional stresses. In this model, the accumulation of tensional stresses induces periods of apparent rise in sea level. These are followed by periods of sea-level lowering, in general of shorter duration, associated with the rapid relaxation of tensional stresses. Hence, in the period just prior to rifting, sea levels should rise and then fall during the continental break-up phase. Such a break-up unconformity is commonly observed in the stratigraphic record of passive margins, as

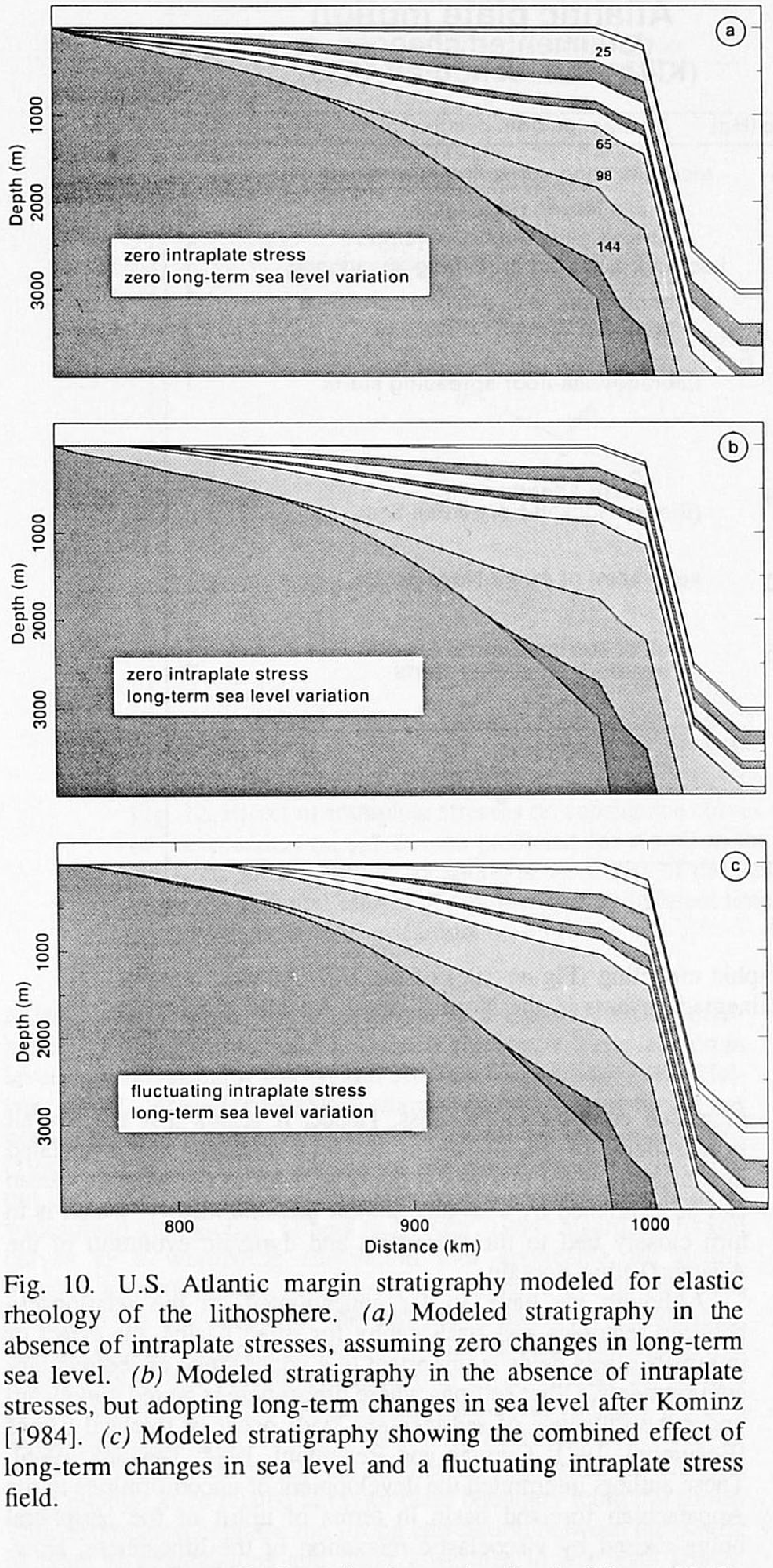

Fig. 10. U.S. Atlantic margin stratigraphy modeled for elastic rheology of the lithosphere. *(a)* Modeled stratigraphy in the absence of intraplate stresses, assuming zero changes in long-term sea level. *(b)* Modeled stratigraphy in the absence of intraplate stresses, but adopting long-term changes in sea level after Kominz [1984]. *(c)* Modeled stratigraphy showing the combined effect of long-term changes in sea level and a fluctuating intraplate stress field.

illustrated by the major lowering in sea level coinciding with the onset of the opening of the South Atlantic [Haq et al., 1987]. These break-up unconformities have not been successfully explained by prior geodynamic models of sedimentary basins, not including the effects of intraplate stresses.

The position of coastal onlap reflects the position where rate of subsidence equals rate of sea-level fall. During application of stress the rate of subsidence is temporarily changed. Consequently, the equilibrium point of the coastal onlap is shifted in position. The thermally induced rate of long-term subsidence strongly decreases with the age of the basin [Turcotte and Ahern, 1977]. Hence, the production of offlaps during late stages of passive margin evolution requires much lower rates of change of sea level than in earlier stages of basin evolution [Thorne and Watts, 1984]. If these offlaps result from fluctuations in intraplate stress levels, the rate of stress changes required diminish with age during the post-rift evolution of the basin. This is of particular relevance for an assessment of the relative contributions of tectonics and eustasy to Cenozoic unconformities. For example, Cenozoic unconformities developed at old passive margins in association with short-term basin narrowing could be produced by relatively mild changes in intraplate stress levels. Such late-stage narrowing of Phanerozoic platform basins and passive margins is frequently observed [Sleep and Snell, 1976], without clear evidence for active tectonism.

Hence, the incorporation of intraplate stresses in elastic models of basin evolution can, in principle, predict a succession of onlaps and offlaps such as observed along the flanks of the U.S. Atlantic margin and the Tertiary North Sea Basin [Kooi et al., 1988]. Such a stratigraphy can be interpreted as a natural consequence of the mechanical widening and narrowing of basins by fluctuations in intraplate stress levels superimposed on the long-term broadening of the basin with cooling since its formation.

Figure 11 shows the paleo-stress field inferred from the modeling of the stratigraphy of the U.S. Atlantic margin. The stress levels given for the elastic models for basin stratigraphy provide upper limits. As discussed in the previous section, the incorporation of depth-dependent rheology in the modeling will lower the predicted stress levels. Similarly, the resolution of the inferred paleo-stress pattern can be enhanced by incorporating more sophisticated sedimentation models and high-resolution paleobathymetry in the analysis [Kooi et al., 1988]. The long-term trend of the paleo-stress pattern is that of a change from overall tension during Cretaceous times to a stress regime of accumulating compression during Tertiary times. Superimposed on this long-term trend are more abrupt changes. Both the character and timing of these changes are largely consistent with independent data on the kinematic evolution of the Central Atlantic [Klitgord and Schouten, 1986]. From 175 Ma- 59 Ma rifting in the Atlantic evolves from the initiation of the Gulf of Mexico - Central Atlantic - Ligurian Tethys spreading (175 Ma), by a number of discrete steps (170, 150, 132, 119, 80, 67 Ma), to the start of spreading in the Northern Atlantic (59 Ma). The paleo-stress curve inferred from the stratigraphy suggests that, in particular, the rifting events around 180 Ma have been associated with a major relaxation of tensional stresses, followed by renewed accumulation of tension. It is interesting to compare the paleo-stress curve for the Tertiary with the tectonic history of the Atlantic. The predicted phase of relaxation of tensional stresses and the transition to a more neutral stress regime around 50 Ma coincides with the termination of the dramatic phase of Thulean volcanism in the northern Atlantic and the break-up in the Greenland-Rockall and Norwegian-Greenland sea [Ziegler, 1988; see also Tucholke and Mountain, 1986]. Similarly, the predicted transition to a more compressional stress regime coincides with the timing of the Caribbean orogeny, the Pyrenean orogeny and the cessation of spreading in the Labrador Sea [Klitgord and Schouten, 1986]. As noted by Issler and Beaumont [1987], sea-floor spreading ended in the Labrador Sea simultaneously with widespread shelf shallowing, tectonism and coastal erosion, features consistent with an increase in the level of compressional stress. The change in the compressional stress level at the time of the mid-Oligocene regression, coincides with a major reorganization in the Central Atlantic: the African plate boundary jump.

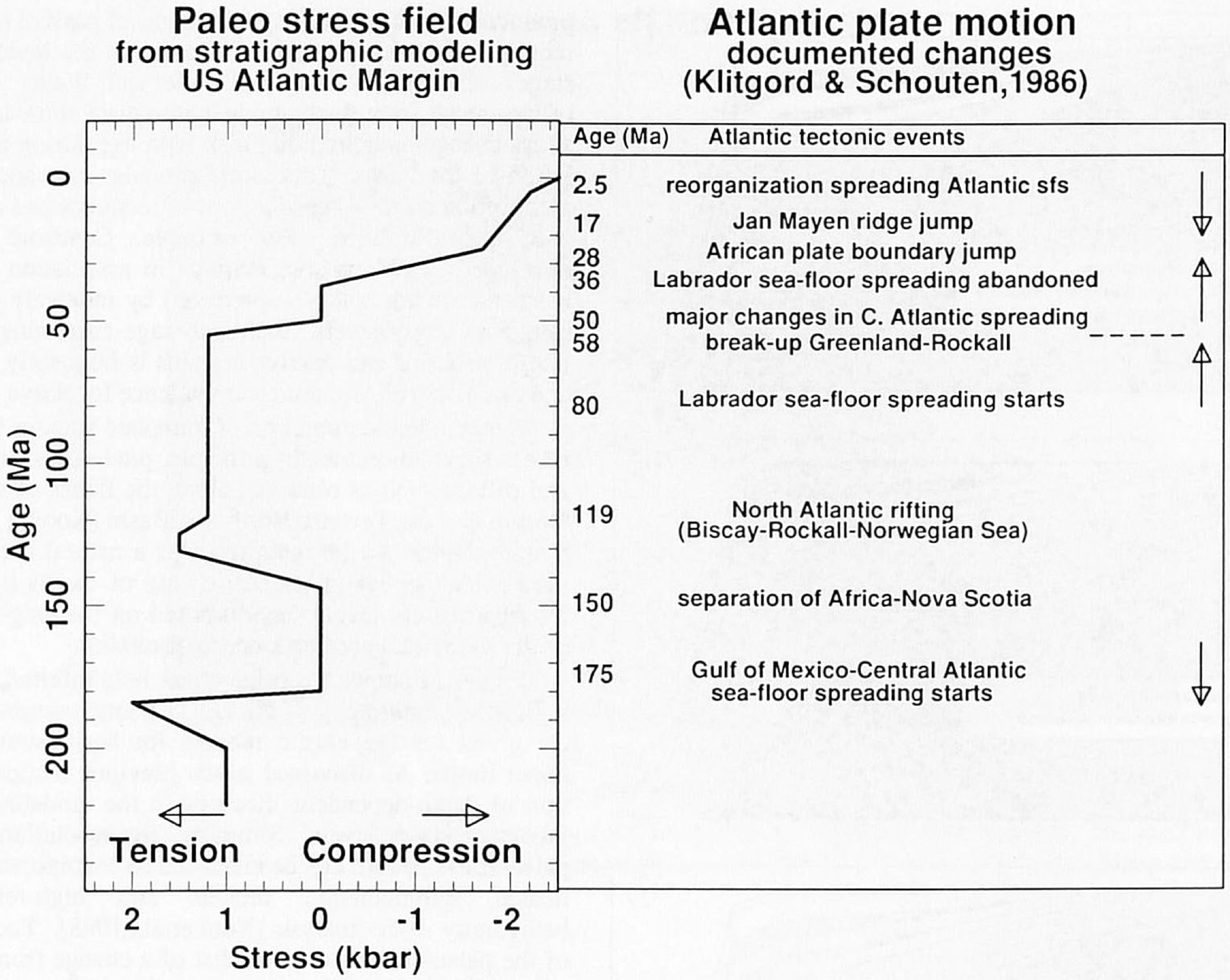

Fig. 11. The paleo-stress curve inferred from the stratigraphic modeling (Figure 10c) of the U.S. Atlantic margin. Tension is positive, compression is negative. Timing of kinematic events in the North/Central Atlantic is given at right [After Klitgord and Schouten, 1986].

Hence, the inferred transition in the horizontal stress field seems to be qualitatively consistent with that expected from the plate kinematics during the same time period. The transition from Mesozoic overall tension to a more compressional regime during Cenozoic times also agrees with a recent stratigraphic study [Hubbard, 1988] on the timing and nature of the sequence boundaries in the Arctic and the Atlantic. This author demonstrated that the majority of Mesozoic sequence boundaries in three rifted continental margin basins are associated with rifting phases, while Cenozoic unconformities in the Arctic correspond to the timing of compressional phases. In this context, it is also interesting to note that a paleo-stress curve derived from the apparent sea-level record of the North Sea area, assuming that the sea levels are controlled by the effects of intraplate stresses, also shows a change from a long-term tensional regime during Jurassic-Cretaceous times to a more compressional stress regime during Tertiary times [Lambeck et al., 1987]. These findings have been recently confirmed by detailed stratigraphic modeling, incorporating the role of intraplate stresses, of the North Sea Central Graben area [Kooi et al., 1988]. The inferred paleo-stress curve is consistent with the transition from rift-wrench tectonics during Mesozoic times to compressional tectonics during Tertiary times in Northwestern Europe [Ziegler, 1982, 1987]. Also, in other respects, the paleo-stress curve appears to mirror the tectonic evolution of Northwestern Europe: rifting episodes correspond to relaxation of tensional paleo-stresses, and Alpine orogenic phases were found to correspond to episodes of increased compressional stress. Hence, it seems that the overall synchroneity in the timing of sea-level changes and associated unconformities for margins at opposite sides of the Atlantic Ocean can be explained by a largely similar tectonic history, which is in turn closely tied to the kinematic and dynamic evolution of the Atlantic/Tethys domain.

Although we have so far concentrated on the relationship between tectonics and stratigraphy for rifted basins, the effect of intraplate stress fields is important to a wider range of sedimentary environments. Other settings where lithosphere is flexed downward under the influence of sedimentary loads occur in foreland basins [Beaumont, 1981; Quinlan and Beaumont, 1984; Tankard, 1986]. These authors interpreted the development of unconformities in the Appalachian foreland basin in terms of uplift of the peripheral bulge caused by viscoelastic relaxation of the lithosphere. However, the presence of tensional or compressional intraplate stresses, the latter being more natural in this tectonic setting, can amplify or reduce the height of the peripheral bulge by an equivalent amount and thus greatly influence the stratigraphic record.

Discrimination of Tectonics and Eustasy

The Exxon curves [Vail et al., 1977; Haq et al., 1987], though based on data from basins throughout the world, are heavily weighted in favor of the Northern Atlantic and the North Sea areas. Therefore, the inferred global cycles may strongly reflect the

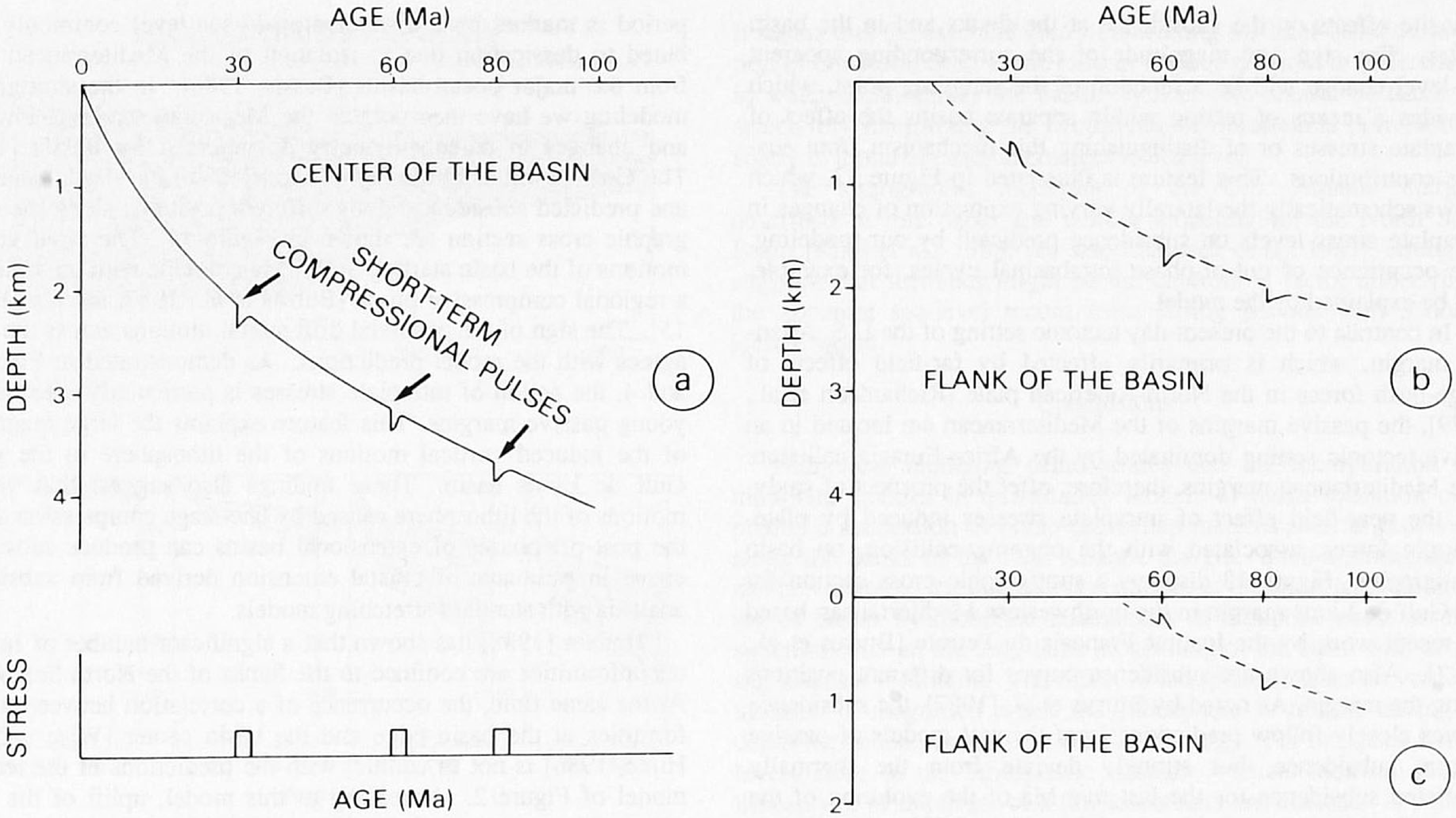

Fig. 12. Effect of intraplate stresses on subsidence curves at three different positions a,b, and c in the basin. *(a)* Effect of compression on subsidence predicted for a well in the basin center. *(b)* and *(c)* show the effect of compressional stress on subsidence for locations at the flanks of the basin, closer to the position of the flexural node. Note in these cases the different effects of compression at different time intervals, which are caused by widening of the basin during its long-term thermal evolution.

seismic stratigraphic record of basins in a tectonic setting dominated by rifting events -and associated changes in intraplate stress levels- in the northern and central Atlantic [e.g., Miall, 1986; Hallam, 1988]. The inferred global character of the Exxon curves has been subject to considerable debate. Parkinson and Summerhayes [1985] and Miall [1986] questioned the global character, pointing out that the synchroneity of the inferred sea-level changes is more widespread than global. Others [e.g., Kerr, 1984] regard the Exxon curves as a worldwide correlation tool applicable for dating mapped unconformities. Similarly, considerable debate has been going on on the causes of the short-term sea-level fluctuations. The question of global synchroneity is also an important one in this respect, as it has played a crucial role in arguments favoring a glacio-eustatic cause for the short-term sea-level changes versus a tectonic origin. Only the larger short-term fluctuations in sea level, with magnitudes in excess of 50 meters, require stress changes large enough to be related to major plate boundary reorganizations. This observation explains the strong correlation between the timing of plate reorganizations and rapid lowerings in sea level [Bally, 1982].

The regional character of intraplate stresses sheds new light on deviations [e.g., Hubbard et al., 1985; Hallam, 1988] from "global" sea-level cycles. Although such deviations are a natural feature of Cloetingh et al.'s [1985] model, the occurrence of short-term deviations does not preclude the presence of global events elsewhere in the stratigraphic record. These are to be expected when major plate reorganizations affect the intraplate stress fields simultaneously in more than one plate or when glacio-eustasy dominates. Examples of major plate reorganizations include those during Mid-Oligocene [Engebretson et al., 1985] and Early Cenozoic [Rona and Richardson, 1978; Schwann, 1985] times. In particular the mid-Oligocene is a time with a high level of tectonic activity in the northern and southern Atlantic, with the concomitant occurrence of a major Alpine folding phase [Ziegler, 1982] and, for example, uplift of the shelf of the African Atlantic margins [Lehner and De Ruiter, 1977]. Furthermore, differences in the rheological structure of the lithosphere, which influence its response to applied intraplate stresses (Figure 4), might also explain differences in the magnitudes of the inferred sea levels such as observed between the North Sea region and the Gippsland Basin off southeastern Australia [Vail et al., 1977].

Independent recent studies of the magnitude of the mid-Oligocene lowering point to a value much smaller than previously thought. The magnitude of this fall in sea level, which is by far the largest shown in the Vail et al. [1977] and Haq et al. [1987] curves, is now estimated to be between 50 [Miller and Fairbanks, 1985; Watts and Thorne, 1984] and 100 [Schlanger and Premoli-Silva, 1986] meters. Hence, a significant part of the short-term sea-level record inferred from seismic stratigraphy might have a characteristic magnitude of a few tens of meters, which can be explained by relatively modest stress fluctuations. The superposition of a glacio-eustatic event and a major tectonic reorganization might explain the exceptional magnitude of the Oligocene sea-level lowering.

The discrimination of regional events from eustatic signals in the sea-level record of individual basins is usually a subtle matter, especially if biostratigraphic correlation is imprecise [Hallam, 1988]. As noted earlier, intraplate stresses cause different and opposite effects on the subsidence at the flanks and in the basin center. The sign and magnitude of the corresponding apparent sea-level change will be a function of the sampling point, which provides a means of testing within separate basins the effect of intraplate stresses or of distinguishing this mechanism from eustatic contributions. This feature is illustrated in Figure 12, which shows schematically the laterally varying expression of changes in intraplate stress levels on subsidence predicted by our modeling. The occurrence of out-of-phase intrabasinal cycles, for example, can be explained by the model.

In contrast to the present-day tectonic setting of the U.S. Atlantic margin, which is primarily affected by far-field effects of ridge-push forces in the North-American plate [Richardson et al., 1979], the passive margins of the Mediterranean are located in an active tectonic setting dominated by the Africa-Eurasia collision. The Mediterranean margins, therefore, offer the prospect of studying the near-field effect of intraplate stresses induced by plate-tectonic forces, associated with the ongoing collision, on basin stratigraphy. Figure 13 displays a stratigraphic cross section for the Gulf de Lions margin in the northwestern Mediterranean based on recent work by the Institut Francais du Petrole [Burrus et al., 1987]. Also shown are subsidence curves for different positions along the margin. As noted by Burrus et al. [1987], the subsidence curves closely follow predictions from thermal models of passive margin subsidence, but strongly deviate from the thermally predicted subsidence for the last five Ma of the evolution of the basin. Rapid excess subsidence of the order of 500 meters is initiated at the basin center, while uplift of the order of a few hundred meters is induced at the shelf (Figure 13). The thick offlap sequences and time-equivalent unconformities in Figure 13 correspond to the Messinian salinity crisis [Bessis, 1986]. This period is marked by a distinct drop in sea level commonly attributed to dessication due to isolation of the Mediterranean basin from the major ocean basins [Bessis, 1986]. In the stratigraphic modeling we have incorporated the Messinian sea-level lowering and changes in paleobathymetry documented by Bessis [1986]. The Gulf de Lions stratigraphy, modeled for an elastic rheology, and predicted subsidence along different positions along the stratigraphic cross section are shown in Figure 14. The rapid vertical motions of the basin starting at 7-5 Ma coincide with the timing of a regional compressive phase [Burrus et al., 1987; see also Figure 15]. The sign of the observed differential motions across the basin agrees with the model predictions. As demonstrated in Figures 3 and 4, the action of intraplate stresses is particularly effective for young passive margins. This feature explains the large magnitude of the induced vertical motions of the lithosphere in the young Gulf de Lions basin. These findings also suggest that vertical motions of the lithosphere caused by late-stage compression during the post-rift phases of extensional basins can produce substantial errors in estimates of crustal extension derived from subsidence analysis with standard stretching models.

Hallam [1988] has shown that a significant number of Jurassic unconformities are confined to the flanks of the North Sea basins. At the same time, the occurrence of a correlation between unconformities at the basin edge and the basin center [Wise and Van Hinte, 1986] is not in conflict with the predictions of the tectonic model of Figure 2. According to this model, uplift of the basin edge with exposure of the inner shelf of passive margins and steepening of the basin slope can be caused by the action of intraplate compressional stresses or, equivalently, by relaxation of a tensional stress regime. As pointed out by Miller et al. [1987], the frequently observed correlation between unconformities on the

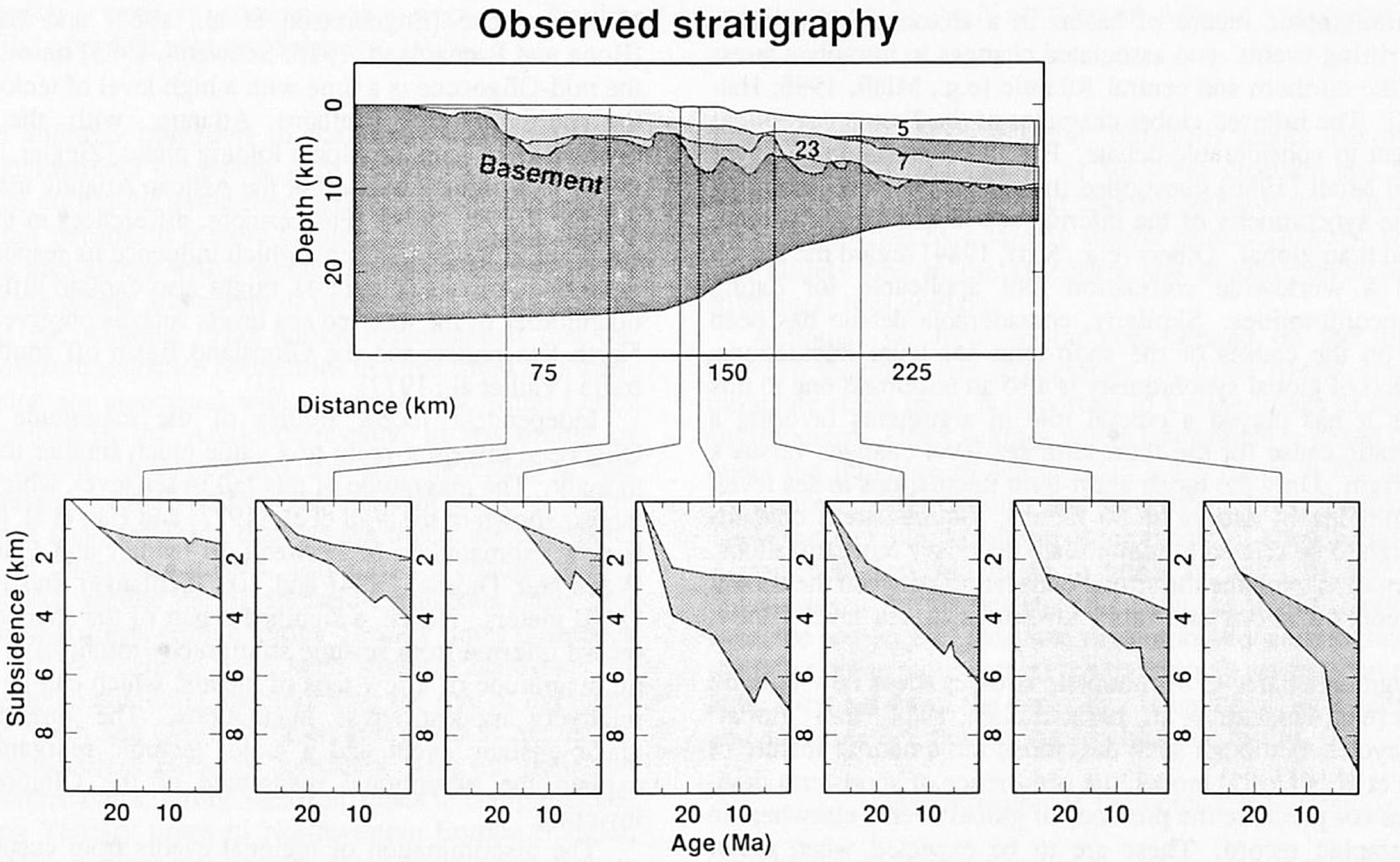

Fig. 13. Stratigraphy Gulf de Lions passive margin (NW Mediterranean). Lower part of the figure shows subsidence curves for different positions along stratigraphic cross section. Shading indicates unloading correction. [After Burrus et al., 1987].

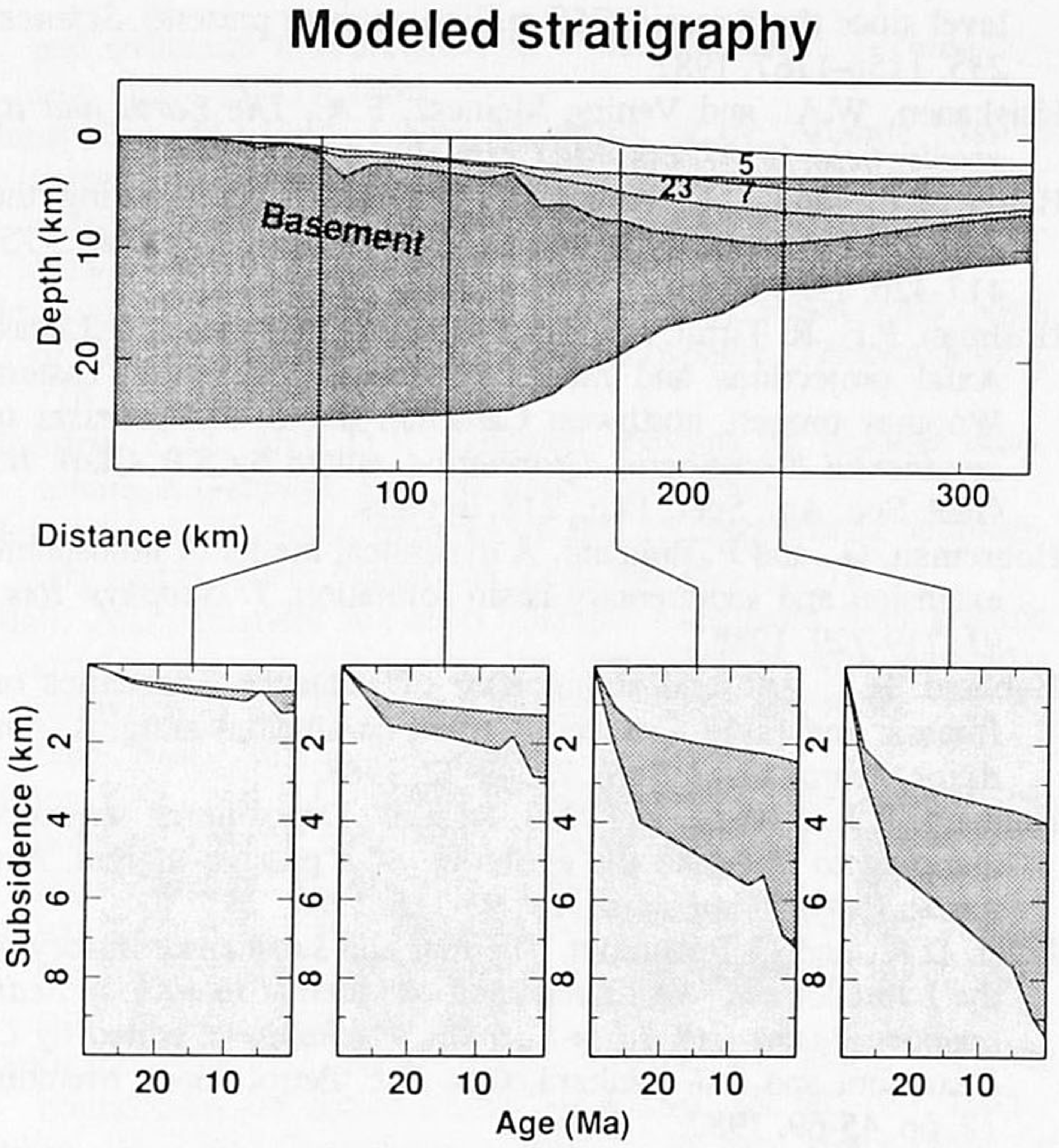

Fig. 14. Modeled stratigraphy Gulf de Lions passive margin for an elastic rheology of the lithosphere, adopting a strong compressive phase starting at the 7-5 Ma time interval. Curves showing predicted subsidence are given in the lower part of the Figure for positions along the modeled stratigraphic cross section.

shelf and in deeper parts of continental margin basins might simply result from subaereal exposure of the shelves. These authors argued that "the material eroded from the exposed shelves could have increased sediment supply to the actually restricted submarine shelf, stimulating increased slope failure and submarine erosion".

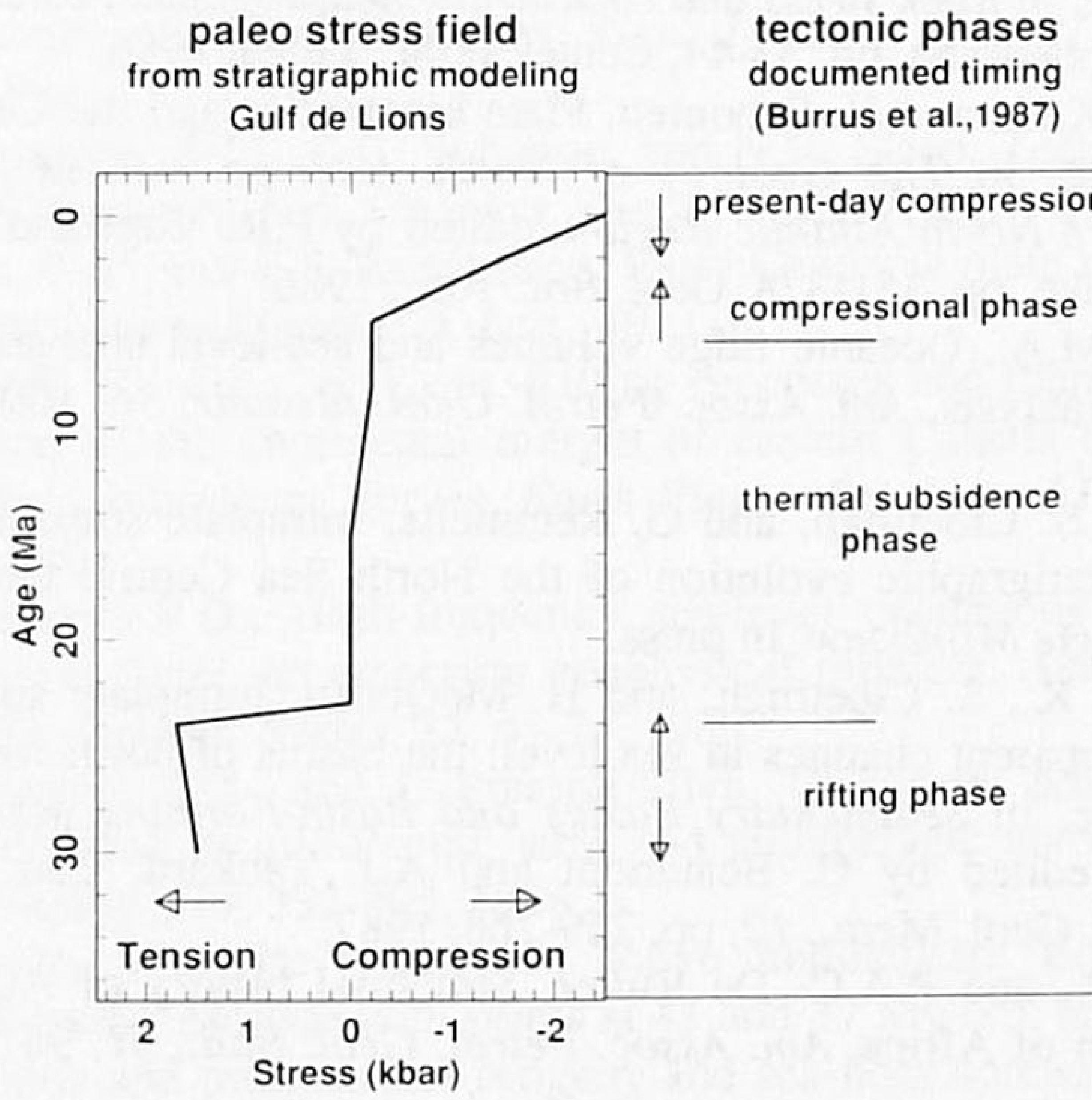

Fig. 15. The paleo-stress field inferred from the stratigraphic modeling (Figure 14) with timing of tectonic phases [After Burrus et al., 1987].

It seems that the essential factor controlling the inter-basin correlation of unconformities is the ratio of surface gradient to differences in water depth across the basin. Hence, care should be taken in selectively interpreting the occurrence of intrabasinal correlations solely in terms of eustatic changes in sea level.

The stratigraphic modeling of the U.S. Atlantic margin described in this paper and similar modeling for the North Sea Basin [Kooi et al., 1988; see also Lambeck et al., 1987], strongly suggests that tectonics might be the controlling factor underlying the apparent sea-level record even during periods with a non-icefree world.

Conclusions

Numerical modeling demonstrates that the incorporation of intraplate stresses in quantitative models of basin evolution can predict a succession of onlap and offlap patterns such as observed along the flanks of the U.S. Atlantic margin. Such a stratigraphy can be viewed as the natural consequence of the short-term narrowing of basins by moderate fluctuations in intraplate stress levels, superimposed on the long-term broadening of the basin with cooling since its formation. The effect of intraplate stresses on vertical motions is magnified when the lithosphere is treated having a depth-dependent, rather than elastic, rheology. For intraplate stress levels close to the lithospheric strength, vertical motions of the lithosphere of the order of a few kilometers are induced. A paleo-stress field inferred from the U.S. Atlantic margin stratigraphy is characterized by a transition from overall tension during Mesozoic times to a regime of more compressional character during Cenozoic times. These findings are in agreement with the outcome of a similar analysis of North Sea Basin stratigraphy and strongly suggest that the short-term apparent sea-level record of the basins at both sides of the Northern and Central Atlantic reflects the tectonic evolution of the Atlantic and global tectonic effects. Differential subsidence across passive margins provides a criterion to discriminate eustatics from tectonism. Stress-induced subsidence and uplift explains the observed record of vertical motions in for example the Gulf de Lions basin.

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References

Bally, A.W., Musings over sedimentary basin evolution, *Philos. Trans Roy. Soc. Lond., A305*, 325-338, 1982.

Beaumont, C., The evolution of sedimentary basins on viscoelastic lithosphere: Theory and examples, *Geophys. J. R. Astron. Soc., 55*, 471-498, 1978.

Beaumont, C., Foreland basins, *Geophys. J. R. Astron. Soc., 65*, 291-329, 1981.

Beaumont, C., C.E. Keen, and R. Boutilier, On the evolution of rifted continental margins: comparison of models and observations for the Nova Scotia margin, *Geophys. J. R. Astron. Soc., 70*, 667-715, 1982.

Beaumont, C., and A.J. Tankard (editors), *Sedimentary Basins and Basin-Forming Mechanisms*, Can. Soc. Petrol. Geol. Memoir, *12*, 527 pp., 1987.

Bell, J.S., and D.I. Gough, Northeast-southwest compressive stress in Alberta: Evidence from oil wells, *Earth Planet. Sci. Lett., 45,* 475-482, 1979.

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

Bergman, E.A., Intraplate earthquakes and the state of stress in oceanic lithosphere, *Tectonophysics, 132,* 1-35, 1986.

Bergman, E.A., and S.C. Solomon, Earthquake source mechanisms from body-waveform inversion and intraplate tectonics in the northern Indian Ocean, *Phys. Earth Planet. Int., 40,* 1-23, 1985.

Bessis, F., Some remarks on the study of subsidence of sedimentary basins, application to the Gulf de Lions margin (Western Mediterranean), *Mar. Petrol. Geol., 3,* 37-63, 1986.

Bodine, J.H., M.S. Steckler, and A.B. Watts, Observations of flexure and the rheology of oceanic lithosphere, *J. Geophys. Res., 86,* 3695-3707, 1981.

Burrus, J., F. Bessis, and B. Doligez, Heat flow, subsidence and crustal structure of the Gulf of Lions (NW Mediterranean): a quantitative discussion of the classical passive margin model, in *Sedimentary Basins and Basin-Forming Mechanisms,* edited by C. Beaumont and A.J. Tankard, Can. Soc. Petrol. Geol. Memoir, *12,* pp. 1-15, 1987.

Byerlee, J.D., Friction of rocks, *Pageoph, 116,* 615-626, 1978

Carter, N.L., and M.C. Tsen, Flow properties of continental lithosphere, *Tectonophysics, 136,* 27-63, 1987.

Cloetingh, S., Intraplate stresses: A new tectonic mechanism for fluctuations of relative sea level, *Geology, 14,* 617-621, 1986.

Cloetingh, S., H. McQueen, and K. Lambeck, On a tectonic mechanism for regional sealevel variations, *Earth Planet. Sci. Lett., 75,* 157-166, 1985.

Cloetingh, S., and F. Nieuwland, On the mechanics of lithospheric stretching and doming: a finite element analysis, *Geologie Mijnbouw, 63,* 315-322, 1984.

Cloetingh, S., and R. Wortel, Regional stress field of the Indian plate, *Geophys. Res. Lett., 12,* 77-80, 1985.

Cloetingh, S., and R. Wortel, Stress in the Indo-Australian plate, *Tectonophysics, 132,* 49-67, 1986.

Cloetingh, S.A.P.L., M.J.R. Wortel, and N.J. Vlaar, Evolution of passive continental margins and initiation of subduction zones, *Nature, 297,* 139-142, 1982.

Cochran, J.R., Effects of finite rifting times on the development of sedimentary basins, *Earth Planet. Sci. Lett., 66,* 289-302.

Engebretson, D.C., A. Cox, and R.G. Gordon, Relative motions between oceanic and continental plates in the Pacific Basin, *Geol. Soc. Am. Spec. Pap., 206,* 56 pp., 1985.

Goetze, C., and B. Evans, Stress and temperature in the bending lithosphere as constrained by experimental rock mechanics, *Geophys. J. R. Astron. Soc., 59,* 463-478, 1979.

Greenlee, S.M., F.W. Schroeder, and P.R. Vail, Seismic stratigraphy and geohistory of Tertiary strata from the continental shelf off New Jersey: Calculation of eustatic fluctuations from stratigraphic data, in *The Geology of North America, I-2, The Atlantic Continental Margin: U.S.,* edited by R.E. Sheridan and J.A. Grow, pp. 399-416, Geol. Soc. Am., 1988.

Gunn, R., A quantitative study of the lithosphere and gravity anomalies along the Atlantic Coast, *J. Franklin Inst., 237,* 139-154, 1944.

Hallam, A., A reevaluation of Jurassic eustasy in the light of new data and the revised Exxon curve, *Soc. Econ. Palaeont. Miner. Spec. Publ., 42,* in press.

Haq, B., J. Hardenbol, and P.R. Vail, Chronology of fluctuating sea level since the Triassic (250 million years to present), *Science, 235,* 1156-1167, 1987.

Heiskanen, W.A., and Vening Meinesz, F.A., *The Earth and its gravity field,* New York, Mc Graw-Hill, 470 pp.

Heller, P.L., and C.L. Angevine, Sea level cycles during the growth of Atlantic type oceans, *Earth Planet. Sci. Lett., 75,* 417-426, 1985.

Hoffman, P.F., R. Tirrul, J.E. King, M.R. St-Onge, and S.B. Lucas, Axial projections and modes of crustal thickening, eastern Wopmay orogen, northwest Canadian shield, in *Processes in continental lithospheric deformation,* edited by S.P. Clark Jr., Geol. Soc. Am. Spec. Pap., 218, in press.

Houseman, G., and P. England, A dynamical model of lithosphere extension and sedimentary basin formation, *J. Geophys. Res., 91,* 719-729, 1986.

Hubbard, R.J., Age and significance of sequence boundaries on Jurassic and Early Cretaceous rifted continental margins, *Am. Assoc. Petrol. Geol. Bull., 72,* 49-72, 1988.

Hubbard, R.J., J. Pape, and D.G. Roberts, Depositional sequence mapping to illustrate the evolution of a passive margin, *Am. Assoc. Petrol. Geol. Mem., 39,* 93-115, 1985.

Issler, D.R., and C. Beaumont, Thermal and subsidence history of the Labrador and West Greenland continental margin, in *Sedimentary Basins and Basin-Forming Mechanisms,* edited by C. Beaumont and A.J. Tankard, Can. Soc. Petrol. Geol. Memoir, *12,* pp. 45-69, 1987.

Jarvis, G.T., and D.P. McKenzie, Sedimentary basin formation with finite extension rates, *Earth Planet. Sci. Lett., 48,* 42-52, 1980.

Johnson, B., and A.W. Bally (editors), Intraplate deformation: characteristics, processes and causes, *Tectonophysics, 132,* 1-278, 1986.

Karner, G.D., Effects of lithospheric in-plane stress on sedimentary basin stratigraphy, *Tectonics, 5,* 573-588, 1986.

Kerr, A.R., Vail's sea-level curves are'nt going away, *Science, 226,* 677-678, 1984.

Kirby, S.H., Rock mechanics observations pertinent to the rheology of the continental lithosphere and the location of strain along shear zones, *Tectonophysics, 119,* 1-27, 1985.

Klein, R.J., and M.V. Barr, Regional state of stress in western Europe, in *Rock stress and rock stress measurements,* edited by O. Stephensson, pp. 33-44, Centek Publ., Lulea, 1986.

Klitgord, K.D., and H. Schouten, Plate kinematics and the Central Atlantic, in *The Geology of North America, vol. M., The Western North Atlantic Region,* edited by P.R. Vogt and B.E. Tucholke, pp. 351-378, Geol. Soc. Am., 1986.

Kominz, M.A., Oceanic ridge volumes and sea-level change - an error analysis, *Am. Assoc. Petrol. Geol. Memoir, 36,* 109-126, 1984.

Kooi, H., S. Cloetingh, and G. Remmelts, Intraplate stresses and the stratigraphic evolution of the North Sea Central Graben, *Geologie Mijnbouw,* in press.

Lambeck, K., S. Cloetingh, and H. McQueen, Intraplate stresses and apparent changes in sea level: the basins of north-western Europe, in *Sedimentary Basins and Basin-Forming Mechanisms,* edited by C. Beaumont and A.J. Tankard, Can. Soc. Petrol. Geol. Mem., *12,* pp. 259-268, 1987.

Lehner, P., and P.A.C. De Ruiter, Structural history of Atlantic margin of Africa, *Am. Assoc. Petrol. Geol. Bull., 61,* 961-981, 1977.

Letouzey, J., Cenozoic paleo-stress pattern in the Alpine foreland

and structural interpretation in a platform basin, *Tectonophysics, 132,* 215-231, 1986.

Manspeizer, W., Early Mesozoic history of the Atlantic passive margin, in *Geological Evolution of the United States Atlantic margin,* edited by C.W. Poag, pp. 1-23, Nostrand Reinhold, New York, 1985.

McAdoo, D.C., C.F. Martin, and S. Poulouse, Seasat observation of flexure: evidence for a strong lithosphere, *Tectonophysics, 116,* 209-222, 1985.

McAdoo, D.C., and D.T. Sandwell, Folding of oceanic lithosphere, *J. Geophys. Res., 90,* 8563-8569, 1985.

McKenzie, D.P., Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett., 40,* 25-32, 1978.

Miall, A.D., Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record, *Am Assoc. Petrol. Geol. Bull., 70,* 131-137, 1986.

Miller, K.G., and R.G. Fairbanks, Oligocene-Miocene global carbon and abyssal circulation changes, *Am. Geophys. Un. Geophys. Monogr., 32,* 469-486, 1985.

Miller, K.G., R.G. Fairbanks, and G.S. Mountain, Tertiary oxygen isotope synthesis, sea-level history, and continental margin erosion, *Paleoceanography, 2,* 1-19, 1987.

Parkinson, N., and C. Summerhayes, Synchronous global sequence boundaries, *Am. Assoc. Petrol. Geol. Bull., 69,* 685-687, 1985.

Philip, H., Plio-Quaternary evolution of the stress field in Mediterranean zones of subduction and collision, *Ann. Geophys., 5B,* 301-320, 1987.

Pitman, W.C. III, and X. Golovchenko, The effect of sea level change on the shelf edge and slope of passive margins, *Soc. Econ. Paleont. Miner. Spec. Publ., 33,* 41-58, 1983.

Poag, C. W., and J.S. Schlee, Depositional sequences and stratigraphic gaps on submerged Unites States Atlantic margin, *Am. Assoc. Petrol. Geol. Memoir, 36,* 165-182, 1984.

Price, R.A., Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, in: *Gravity and Tectonics,* edited by K.A. deJong and R. Scholten, pp. 491-502, Wiley, New York, 1973.

Quinlan, G.M., and C. Beaumont, Appalachian thrusting, lithospheric flexure and the Paleozoic stratigraphy of the eastern interior of North America, *Can. J. Earth Sci., 21,* 973-996, 1984.

Richardson, R.M., S.C. Solomon, and N.H. Sleep, Tectonic stress in the plates, *Rev. Geophys. Space Phys., 17,* 981-1019, 1979.

Rona, P.A., and E.S. Richardson, Early Cenozoic plate reorganization, *Earth Planet. Sci. Lett., 40,* 1-11.

Royden, L., and C.E. Keen, Rifting processes and thermal evolution of the continental margin of eastern Canada determined from subsidence curves, *Earth Planet. Sci. Lett., 51,* 343-361, 1980.

Schlanger, S.O., High-frequency sea-level oscilations in Cretaceous time: an emerging geophysical problem, *Am. Geophys. Un. Geodyn. Series, 15,* 61-74, 1986.

Schlanger, S.O., and I. Premoli-Silva, Oligocene sealevel falls recorded in mid-Pacific atoll and archipelagic apron settings, *Geology, 14,* 392-395, 1986.

Schwan, W., The worldwide active middle/Late Eocene geodynamic episode with peaks at 45 and 37 My b.p. and implications and problems of orogeny and sea-floor spreading, *Tectonophysics, 115,* 197-234, 1985.

Shudofsky, G.S., S. Cloetingh, S. Stein, and R. Wortel, Unusually deep earthquakes in East Africa: constraints on the thermomechanical evolution of a continental rift system, *Geophys. Res. Lett., 14,* 741-744, 1987.

Sleep, N.H., Thermal effects of the formation of Atlantic continental margins by continental break up, *Geophys. J. R. Astron. Soc., 24,* 325-350, 1971.

Sleep, N.H., and N.S. Snell, Thermal contraction and flexure of mid-continent and Atlantic marginal basins, *Geophys. J. R. Astron. Soc., 45,* 125-154, 1976.

Smoluchowski, M., Uber eine gewisse Stabilitatsproblem der Elasticitatslehre und dessem Beziehung zur Entstehung Faltengebirge, *Bull. Int. Ac. Sci. Cracovie, 2,* 3-20, 1909.

Steckler, M.S., and U.S. Ten Brink, Lithospheric strength variations as a control on new plate boundaries: examples from the northern Red Sea region, *Earth Planet. Sci. Lett., 79,* 120-132, 1986.

Steckler, M.S., A.B. Watts, and J.R. Thorne, Subsidence and basin modeling at the U.S. Atlantic passive margin, in *The Geology of North America, v. I-2, The Atlantic Continental Margin: U.S.,* edited by R.E. Sheridan and J.A. Grow, pp. 399-416, Geol. Soc. Am., 1988.

Stephenson, R., and K. Lambeck, Isostatic response of the lithosphere with in-plane stress: Application to central Australia, *J. Geophys. Res., 90,* 8581-8588, 1985.

Tankard, A.J., Depositional response to foreland deformation in the Carboniferous of eastern Kentucky, *Am. Assoc. Petrol. Geol. Bull., 70,* 853-868, 1986.

Thorne, J., and Watts, A.B., Seismic reflectors and unconformities at passive continental margins, *Nature, 311,* 365-368, 1984.

Tucholke, B.E., and G.S. Mountain, Tertiary paleoceanography of the western north Atlantic Ocean, in *The Geology of North America, vol. M., The Western North Atlantic Region,* edited by P.R. Vogt and B.E. Tucholke, pp. 631-650, Geol. Soc. Am., 1986.

Turcotte, D.L., and J.L. Ahern, On the thermal and subsidence history of sedimentary basins, *J. Geophys. Res., 82,* 3762-3766, 1977.

Turcotte, D.L., and G. Schubert, *Geodynamics,* 450 pp., Wiley, New York, 1982.

Vail, P.R., R.M. Mitchum Jr., and S. Thompson III, Global cycles of relative changes of sea level, *Am. Assoc. Petrol. Geol. Memoir, 26,* 83-97, 1977.

Verwer, J.G., A class of stabilized three-step Runge-Kutta methods for the numerical integration of parabolic equations, *J. Comp. Appl. Math., 3,* 155-166, 1977.

Vink, G.E., W.J. Morgan, and W.L. Zhao, Preferential rifting of continents: a source of displaced terranes, *J. Geophys. Res., 89,* 10072-10076, 1984.

Wamel, W.A. van, On the tectonics of the Ligurian Apennines (northern Italy), *Tectonophysics, 142,* 87-98, 1987.

Watts, A.B.,Tectonic subsidence, flexure and global changes of sea level, *Nature, 297,* 469-474, 1982.

Watts, A.B., G.D. Karner, and M.S. Steckler, Lithospheric flexure and the evolution of sedimentary basins, *Philos. Trans. R. Soc. Lond., A305,* 249-281, 1982.

Watts, A.B., and J.Thorne, Tectonics, global changes in sea level and their relationship to stratigraphical sequences at the U.S. Atlantic continental margin, *Mar. Petr. Geol., 1,* 319-339, 1984.

Weissel, J.K., Anderson, R.N., and Geller, C.A., Deformation of the Indo-Australian plate, *Nature, 287,* 284-291, 1980.

Wiens, D.A., and Stein, S., Age dependence of oceanic intraplate seismicity and implications for lithospheric evolution, *J. Geophys. Res.*, *88*, 6455-6468, 1983.

Wiens, D.A., and Stein, S., Intraplate seismicity and stresses in young oceanic lithosphere, *J. Geophys. Res.*, *89*, 11442-11464, 1984.

Wise, S.W., J.E. Van Hinte, et al., Mesozoic-Cenozoic depositional environment revealed by Deep Sea Drilling Project Leg 93 drilling on the continental rise of the eastern Unites States: *Geol. Soc. Spec. Publ.*, *21*, 35-66, 1986.

Wortel, R., and S. Cloetingh, On the origin of the Cocos-Nazca spreading center, *Geology*, *9*, 425-430, 1981.

Wortel, R., and S. Cloetingh, A mechanism for fragmentation of oceanic plates, *Am. Assoc. Petrol. Geol. Memoir*, *34*, 793-801, 1983.

Ziegler, P.A., *Geological Atlas of Western and Central Europe*, 130 pp., Shell Int. Petrol. Mij (The Hague)/ Elsevier (Amsterdam), 1982.

Ziegler, P.A., Intraplate compressional deformations in the Alpine foreland - a geodynamic model, *Tectonophysics*, *137*, 389-420, 1987.

Ziegler, P.A., Evolution of the Arctic-North Atlantic and the western Tethys, *Am. Assoc. Petrol. Geol. Memoir*, *43*, 1988.

Ziegler, P.A., Post-Hercynian plate reorganization in the Tethys and Arctic North Atlantic, in *Triassic-Jurassic rifting in North-America-Africa*, edited by W. Manspeizer, Elsevier, Amsterdam, in press.

Zoback, M.D., Wellbore break-out and in-situ stress, *J. Geophys. Res.*, *90*, 5523-5530, 1985.

Zuber, M.T., Compression of oceanic lithosphere: an analysis of intraplate deformation in the Central Indian Ocean Basin, *J. Geophys. Res.*, *92*, 4817-4825, 1987.