INTRAPLATE STRESSES: A NEW PERSPECTIVE ON QDS AND VAIL’S THIRD-ORDER CYCLES

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ABSTRACT

Fluctuation in lithospheric stresses is an important tectonic component of quantitative dynamic basin stratigraphy, and provides a tectonic explanation for Vail’s third-order cycles in apparent sea levels. The gross onlap/offlap stratigraphic architecture of passive margin basins can be simulated by models with changing horizontal stress fields. Modeling 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. Out-of-phase intrabasinal cycles with, for example, relative uplift at the flanks and increased subsidence at the basin center, such as the case for the Gulf de Lions margin, also are predicted by the models. The large variations in estimates of magnitudes of short-term changes in relative sea level between various basins around the globe are in agreement with predictions of this tectonic model.

INTRODUCTION

During the last decade of substantial progress in geodynamic modeling, the role of thermomechanical properties of the lithosphere has been emphasized in models of sedimentary basin evolution (e.g., Watts et al., 1982; Beaumont et al., 1982; Beaumont and Tankard, 1987). These models have assessed the contributions of a variety of lithospheric processes to the vertical motions of lithosphere within 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 (Beaumont, 1978).

Simultaneously, major advances have been made in understanding the origins and distributions of stress fields in plate interiors. Detailed analysis of earthquake focal mechanisms (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 paleostress fields in the lithosphere by analysis of microstructures...
(Letouzey, 1986; Bergerat, 1987; Philip, 1987) have demonstrated 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 paleostress fields, and has shown (see Philip, 1987) that the state of stress can vary enough to produce quite different deformations on a relatively short time scale (approximately 5 m.y.). 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 orientations in 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).

Although intraplate stresses play a crucial role during basin formation, their effect on the subsequent evolution of sedimentary basins largely has been ignored. 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). Recent work by Cloetingh et al. (1985), Cloetingh (1986, 1988) and Karner (1986) has demonstrated that temporal fluctuations in intraplate stresses have important consequences for quantitative dynamic basin stratigraphy and may provide a tectonic explanation for short-term sea-level variations inferred from the stratigraphic record (Vail et al., 1977; Haq et al., 1987).

Simultaneously, we have explored (Cloetingh, 1986; Lambeck et al., 1987) using the stratigraphic record as a source of information on paleostress fields. Vail and co-workers have attributed cyclic variations in onlap/offlap stratigraphic patterns to glacially induced or other eustatic origins. This preference was based primarily on the inferred global synchronicity of sea-level variations, and the lack of a tectonic explanation for observed third-order cycles. Although other authors (e.g., Bally, 1982; Watts, 1982) argued for a tectonic cause of 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, may be the lack of significant Mesozoic and Cenozoic glaciation prior to the mid-Tertiary (Pitman and Golovchenko, 1983). In the absence of a glacio-eustatic control, possible tectonic, sediment yield or other climatic controls might be postulated. Plate dynamics and associated changes in stress levels in plate interiors offer a tectonic framework for observed short-term relative sea-level variations and are a parameter of concern to quantitative dynamic stratigraphy. Mechanisms for long-term changes in sea level (e.g., Heller and Angevine, 1985; Kominz, 1984) are beyond the scope of the present paper.

**Intraplate Stress and Quantitative Dynamic Stratigraphy**

Intraplate stresses modulate basin deflections caused by the primary driving mechanisms of basin subsidence as, for example, thermal contraction of the lithosphere amplified by sediment loading. Cloetingh et al. (1985) modeled a passive margin evolving through time in response to changing thermal regime and loading by sediments (Fig. 1a). They showed that vertical deflections of the lithosphere of up to a hundred meters may be induced by the action of horizontal stresses in the lithosphere with magnitudes up to a few kbars. They proposed
that basement deflections induced by short-term changes in horizontal stress associated with changes in plate-tectonic regimes are capable of producing not only the magnitude but also the rate of Vail's short-term changes in apparent sea level. Figure 1b shows that the stress-induced subsidence/uplift perturbations change sign and magnitude with intrabasinal position, which provides a means to discriminate between this tectonic effect and eustatic contributions to the apparent sea level. The occurrence of out-of-phase intrabasinal cycles (see also Embry, 1988), for example, can be explained by this tectonic model. It is important to realize that the model relies on stress changes—from the perspective of the model a reduction in compression is equivalent to an increase in tension, and vice versa. An increase in compression, or equivalently a reduction of tension, causes relative uplift of the basin flank and increased subsidence at the basin center, whereas a reduction in compression, or equivalently an increase in tension, induces the opposite effect.

Figure 1. 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).
To model passive margin processes, we considered an elastic lithosphere that cools with time after basin formation. Thus the response of the lithosphere to changes in intraplate stress field is time-dependent, not only because the sediment load increases with time, but also because of the changing mechanical properties of the lithosphere. Although sufficiently large to explain Vail’s third-order cycles, the values for stress-induced basement deflections given in Figure 1b are conservative estimates, being based on an elastic model for the mechanical properties of the lithosphere. The incorporation of a more realistic (weaker) brittle-ductile rheology of the lithosphere based on extrapolation of rock-mechanics data (Goetze and Evans, 1979) significantly magnifies the values of the stress-induced differential motions within the basins.

Figure 2 illustrates the relative movement between sea level and the lithosphere at the flank of a flexural basin immediately landward of the principal sediment load as predicted by numerical calculations (Cloetingh et al., 1985) given for the elastic plate model. The synthetic stratigraphy at the basin edge is shown for three situations: long-term flexural widening of the basin with cooling (Watts, 1982) in the absence of an intraplate stress field (Fig. 2a); the same with a superimposed stress change to 500 bar compression at 50 Ma (Fig. 2b); and the same with a superimposed stress change to 500 bar tension at 50 Ma (Fig. 2c). As noted by Watts (1982), the thermally induced flexural widening of the basin (see Fig. 2a) provides an adequate explanation for long-term phases of coastal onlap. However, because it is a long-term change, it does not produce the punctuated character of sedimentary basin stratigraphy characterized by a succession of alternating rapid onlap and offlap phases. Inspection of Figures 2b and c demonstrates that the incorporation of intraplate stresses in geodynamic models of basin evolution can successfully produce sequence boundaries and the overall onlap/offlap characteristics associated with a punctuated stratigraphy.

Here we concentrate on the relationship between tectonics and stratigraphy of rifted basins, in particular the U.S. Atlantic margin, the North Sea and the Gulf de Lions. However, the effect of intraplate stress fields is equally important to other basins, such as foreland basins where lithosphere is flexed downward by sedimentary loads (Beaumont, 1981; Quinlan and Beaumont, 1984; Tankard, 1986). These authors interpreted unconformities in the Appalachian foreland basin as products of uplift of the peripheral bulge caused by viscoelastic relaxation of the lithosphere. However, intraplate tensional or compressional stresses, of which the latter is more natural in this tectonic setting, can amplify or reduce the height of the peripheral bulge by an equivalent amount and equally influence the stratigraphic record in foreland basins.

Figure 2. 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.
Stratigraphic Modeling of the U.S. Atlantic Margin

As demonstrated by Figure 2, the incorporation of intraplate stresses in elastic models of basin evolution predicts a succession of onlaps and offlaps characteristic of strata along the flanks of basins such as the U.S. Atlantic margin (Sleep and Snell, 1976; see Fig. 3). We selected the U.S. Atlantic margin for a numerical simulation of the observed stratigraphy for several reasons. The U.S. Atlantic margin stratigraphy has been extensively documented (e.g., Poag, 1985), and its evolution has been quantitatively modeled (Sleep and Snell, 1976; Watts and Thorne, 1984; Steckler et al., 1988). Sleep and Snell (1976) proposed a viscoelastic 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 global long-term and short-term sea-level fluctuations throughout the basin evolution. Our modeling approach resembles those by Watts and Thorne (1984) and Steckler et al. (1988) in that we adopt a stretching model for basin initiation, but differs by incorporating the effects of finite and multiple stretching phases and intraplate stresses. We use a finite-difference approach for the thermal calculations as discussed by (Verwer, 1977).

Figure 3. Stratigraphic cross section of the United States Atlantic shelf at Cape Hatteras. The shelf break is about 40 km from the right of the figure. Ages of stratigraphic unit boundaries are given in Ma (After Sleep and Snell, 1976).
Although of limited impact for the late-stage development of the U.S. Atlantic margin, 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 about 180 Ma (Manspeizer, 1985; Ziegler, 1988). Thus the initiation of subsidence is associated with a long period of rifting and stretching. Jurassic sediments were deposited only in 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 may have been very large is evident from the long duration (approximately 36 m.y.) 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 U.S. Atlantic margin (Greenlee et al., 1988) support the occurrence of multiple stretching phases. Therefore, we have adopted both subcrustal attenuation and a minor second stretching phase acting from 131-119 Ma. We also assume that as the basement subsides, the equilibrium profile of the margin will be maintained by sediments that fill 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°C isotherm—in the absence of intraplate stresses and ignoring eustatic changes is shown in Figure 4a. This figure demonstrates the well-known failure of conventional elastic models of basin evolution to predict basin narrowing with younger sediments restricted to the basin center. The observed narrowing of the basin during its late-stage evolution has been interpreted in previous modeling studies as either reflecting the response of the basin to a phase of visco-elastic relaxation (Sleep and Snell, 1976) or the response to a long-term eustatic fall (Watts and Thorne, 1984; Steckler et al., 1988). The total thickness of the Cenozoic sediments provides an independent constraint for the magnitude of the proposed long-term sea-level fall. From our modeling we obtain an upper estimate of approximately 100 m for the post-Late Cretaceous long-term lowering in sea level. We, therefore incorporated a long-term sea-level curve with a Late Cretaceous highstand of 100 m, a curve equivalent to the minimum curve of Kominz (1984). Inspection of the resulting stratigraphic model (Fig. 4b) demonstrates that, although the incorporation of long-term changes in sea level contributes to the Cenozoic narrowing of the margin, the long-term post-Late Cretaceous decline in sea level alone does not produce both the documented basin narrowing and the total thickness of sediments accumulated during this time. We propose that a large part of the observed non depositional or erosional character of the shelf surface is caused by stress-induced uplift of the margin flank. Similarly, short-term changes in intraplate stress levels can produce the Early Eocene and Oligocene offlap phases. Figure 4c shows the best fit to the observed stratigraphy incorporating long-term sea-level changes after Kominz's (1984) minimum curve and a fluctuating intraplate stress field in the stratigraphic modeling. The observed stratigraphy can be simulated by relaxation of tensional intraplate stress fields during Mesozoic times and a post-Cretaceous transition to compressional stress, the level of which increases with time during the Tertiary.

Prior to rifting, eventually followed by continental break-up, tensional stresses increase. For example, rifting in the Southern Atlantic was not an instantaneous process, but occurred
as discrete rift phases with accompanying reduction of accumulated tectonic stresses. This process might explain the enigmatic occurrence of high-frequency sea-level fluctuations during the Cretaceous 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 along both sides of the Atlantic might be an expression of rifting-related accumulation and relaxation of tectonic stresses. According to this view, increases of tectonic stresses induce periods of apparent sea-level rise. These are followed by periods of sea-level lowering of shorter duration that are associated with the rapid relaxation of tectonic stresses. Hence, in the period just prior to rifting, sea level should rise gradually. A major sea-level fall then occurs rapidly during the continental break-up phase. This predicted break-up unconformity commonly is observed in the stratigraphic record of passive margins, and a major lowering in sea level that coincides with the onset of the opening of the South Atlantic is shown in the Haq et al. (1987) curves. It is interesting to note that a break-up unconformity generally is not predicted by geodynamic models of sedimentary basins that do not incorporate intraplate stresses.

In summary, the incorporation of intraplate stresses in elastic models of basin evolution can, in principle, predict a succession of onlaps and offlips such as observed along the flanks of the U.S. Atlantic margin and the Tertiary North Sea Basin (Kooi et al., 1988). This stratigraphic geometry can be interpreted as a natural consequence of short-term phases of mechanical widening and narrowing of basins by fluctuations in intraplate stress levels superimposed on the long-term broadening of the basin induced by cooling after its formation.

**Paleostress from Stratigraphic Modeling: U.S. Atlantic Margin and the Central North Sea**

Figure 5 shows the paleostress field inferred from the stratigraphic model presented above. The stress levels used in elastic models for basin stratigraphy provide upper limits, as the incorporation of depth-dependent rheology (Goetze and Evans, 1979) in the models will lower the predicted stress levels. Similarly, the resolution of the paleostress curve is affected by the quality of the adopted sedimentation models and the availability of high-resolution paleobathymetric data. The long-term trend of the paleostress pattern is from overall tension during the Cretaceous to a stress regime of accumulating compression during the Tertiary. Superimposed on this long-term trend are more abrupt and shorter duration changes. Both the character of these changes and their timing are largely consistent with independent data on the kinematic evolution of the Central Atlantic (Klitgord and Schouten, 1986). Rifting in the Atlantic evolved from initiation of sea-floor spreading in the Gulf of Mexico–Central Atlantic–Ligurian Tethys at 175 Ma, and proceeded by a number of discrete steps (170, 150,
132, 119, 80, 67 Ma) to the start of spreading in the Northern Atlantic at 59 Ma. The paleostress curve inferred from the stratigraphic model suggests that rifting events during the period from about 180 to 140 Ma were associated with a major relaxation of tectonics stresses, followed by a phase of renewed accumulation of tension. The paleostress curve for the Tertiary is of particular interest for a detailed comparison with the documented tectonic history of the Atlantic. The predicted phase of relaxation of tectonics stresses and the transition to a more neutral stress regime around 50 Ma coincides with the termination of Thulean volcanism in the Northern Atlantic, the break-up of the Greenland-Rockall and Norwegian-Greenland sea (P.A. Ziegler, personal communication, 1988; see also Tucholke and Mountain, 1986), and the Eocene compressional phases in the Arctic Sverdrup Basin.

**Figure 5.** The paleo-stress curve inferred from the stratigraphic modeling (Fig. 4c) of the U.S. Atlantic margin. Tension is positive, compression is negative. Timing of kinematic events in the North/Central Atlantic is given at the right hand side (After Klitgord and Schouten, 1986).
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(Embry, 1988). 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, consistent with an increase in the level of compressional stresses. The change in the compressional stress level at the time of the mid-Oligocene regression (Fig. 5), coincides with a major reorganization in the Central Atlantic—the African plate boundary jump.

The paleostress 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, shows a similar change from a long-term regime of overall tension during the Jurassic and Cretaceous to a regime of more compressional character during the Tertiary (Lambeck et al., 1987). These findings were confirmed recently by detailed stratigraphic modeling of the North Sea Central Graben, that incorporated the role of intraplate stresses (Kooi et al., 1988). The inferred paleostress curve (Fig. 6) is consistent with the observed transition from rift-wrench tectonics during the Mesozoic to compressional tectonics during the Tertiary in northwestern Europe (Ziegler, 1982). The paleostress curve appears to mirror the tectonic evolution of northwestern Europe in other respects as well: rift episodes correspond to relaxation of tensional paleostresses, and Alpine orogenic phases correspond to episodes of increased compressional stress. From Late Eocene to Early Oligocene a stress regime of more tensional character is predicted concomitant with the timing of rifting in the European platform, an event that has inhibited to a large extent propagation of compressional stresses induced by Alpine collision into the North Sea area (Ziegler, 1982). As shown by Figure 6, this tensional phase and the predicted overall increase in the level of the post-Early Oligocene compression is consistent with paleostress data from the northwestern European platform (Letouzey, 1986; Bergerat, 1987).

These data demonstrate a large-scale rotation of the paleostress 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 almost perpendicular to the strike of the modeled Central Graben Basins (Klein and Barr, 1986; Kooi et al., 1988). Similarly, the paleostress curve inferred from the stratigraphic modeling is compatible with observed correlations between the timing of unconformities in northwestern European platform basins and documented changes (Livermore and Smith, 1985; Savostin et al., 1986) in the kinematic evolution of the Tethys belt.

**INTERBASINAL VARIATIONS IN MAGNITUDES OF RELATIVE SEA LEVEL**

Although the Exxon curves (Vail et al., 1977; Haq et al., 1987) are based on data from basins throughout the world, they are heavily weighted toward the Northern Atlantic and North Sea areas. As noted by several authors (e.g., Miall, 1986; Hubbard, 1988; Hallam, 1988), the inferred global cycles may primarily reflect the seismic stratigraphic record of basins in a tectonic setting dominated by rifting events in the northern and central Atlantic. Summerhayes (1986) and Miall (1986) questioned the global character of the Exxon curves, pointing out that the synchronicity of the inferred sea-level changes may be widespread, but not necessarily global. Others (e.g., Kerr, 1984) regard the Exxon curves as applicable for
worldwide correlation of unconformities. Similarly, there has been little agreement about the causes of short-term sea-level fluctuations. The assumption of global synchronicity has played a crucial role in arguments favoring a glacio-eustatic or a tectonic cause for short-term sea-level changes. Only fluctuations in sea level with magnitudes in excess of 50 m require stress changes of a magnitude to be related to major reorganizations at convergent plate boundaries, fragmentation of plates or collision processes. This observation explains the existence of the correlation noted by Bally (1982) in timing of plate reorganizations and rapid lowerings in sea level.

The regional character of intraplate stresses provides a basis for alternative interpretations of observed deviations from "global" sea-level cycles (e.g., Hubbard et al., 1985; Hallam, 1988; Embry, 1988). Whereas such deviations from a global pattern are a natural feature of our tectonic model (Cloetingh et al., 1985; Cloetingh, 1988), the occurrence of short-term deviations does not preclude the presence of global events elsewhere in the stratigraphic record. These are expected when major plate reorganizations and changes in intraplate stress fields occur simultaneously in more than one plate or when glacio-eustasy dominates. Major plate reorganizations occurred during the Mid-Oligocene (Engebretson et al., 1985) and the Early Cenozoic (Rona and Richardson, 1978; Schwann, 1985). The mid-Oligocene is a particularly tectonically active time in the northern and southern Atlantic, with the concomitant occurrence of a major Alpine folding phase (Ziegler, 1982) and uplift of the shelf along the Atlantic margins of Africa (Lehner and de Ruiter, 1977). Furthermore, differences in rheological structure of the lithosphere, which influence its response to applied intraplate stresses, might also explain differences in magnitudes of inferred sea levels such as observed between time-equivalent changes in the Tertiary North Sea region and the Gippsland Basin off southeastern Australia (Vail et al., 1977), and between the Jurassic North Sea and the Canadian Sverdrup Basin (Embry, 1988).

The decay of thermal subsidence with time after a heating or rifting event also has consequences for the magnitude of stress-induced sea-level changes. The position of coastal onlap reflects the position where the rate of subsidence equals the rate of sea-level fall. During application of stress the rate of subsidence is temporarily changed, and consequently the equilibrium point of the coastal onlap is shifted in position. The thermally induced rate of long-term subsidence decreases exponentially with age (Turcotte and Ahern, 1977). As noted by Thorne and Watts (1984), the production of offlapping stratigraphic geometries during late stages of passive margin evolution requires much lower rates of sea-level change than those needed to produce offlapping geometries during earlier stages of basin evolution. If these offlapping geometries are caused by fluctuations in intraplate stress levels, then the rate of changes of stress needed to create them also diminish with age during the flexural evolution of the basin. This is particularly relevant for assessing the relative contributions of tectonics and eustasy as a cause for 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.

**Figure 6.** Synthetic paleo-stress curve as inferred from the stratigraphic modeling of the Central North Sea Basin (After Kooi et al., 1988). Also shown in this column are paleo-stress orientation data from Bergerat (1987). The columns on the right show Africa relative to Europe plate motion data from Savostin et al. (1986) and Livermore and Smith (1985).
Independent studies of the magnitude of the mid-Oligocene sea-level lowering indicate a value much smaller than previously thought. The magnitude of this sea-level fall, which is by far the largest shown in the Vail et al. (1977) and Haq et al. (1987) curves, is now estimated as between 50 m (Miller and Fairbanks, 1985; Watts and Thorne, 1984) and 100 m (Schlanger and Premoli-Silva, 1986). 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.

**INTRABASINAL VARIATIONS IN THE DEVELOPMENT OF SEQUENCES**

Discriminating regional tectonic events from eustatic signals in the stratigraphic record of individual basins is usually difficult, especially if biostratigraphic correlation is imprecise (Hallam, 1988). As noted previously, intraplate stresses cause opposite subsidence histories at the flanks and in the centers of basins. Because the sign and magnitude of the corresponding apparent sea-level change is a function of position within a basin, there is a means for testing within separate basins the effect of intraplate stresses and of distinguishing this mechanism from eustatic contributions. As an example, Figure 7 shows schematically the laterally varying expression of changes in intraplate stress levels on subsidence predicted by our modeling. For additional stratigraphic criteria that may discriminate stress-induced tectonic from eustatic controls on depositional cycles, see Embry (1988).

![Diagram](attachment:image.png)

**Figure 7.** Effect of intraplate stresses on subsidence curves at three different positions a, b, and c in a rifted 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.
In contrast to the present-day tectonic setting of the U.S. Atlantic margin, which is affected primarily 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, are natural laboratories for studying near-field effects on basin stratigraphy of intraplate stresses associated with collision. Figure 8 is a stratigraphic cross section of the Gulf de Lions margin in the northwestern Mediterranean based on recent work at the Institut Francais du Petrole (Burris et al., 1987). Also shown are subsidence-history curves for different positions along the margin. As noted by Burris et al. (1987), the subsidence curves conform to predictions from thermal models of passive margin subsidence, except for the last 5 m.y. where they deviate markedly from the thermally predicted subsidence. Rapid excess subsidence of about 500 m occurred at the basin center, while uplift of a few hundred meters occurred at the shelf (Fig. 8). The thick offlap sequences and time-equivalent unconformities shown in Figure 8 correspond to the Messinian salinity crisis, a period marked by a drop in Mediterranean sea level and commonly attributed to its desiccation due to isolation of the Mediterranean from the major ocean basins (Bessis, 1986). In the stratigraphic modeling we have incorporated the Messinian sea-level drop and changes in paleobathymetry documented by Bessis (1986). The stratigraphy modeled assuming an elastic rheology of the lithosphere and incorporating a fluctuating intraplate stress level is displayed in Figure 9. The sign of the observed differential motions across the basin agrees with model predictions. Rapid vertical motions of the basin starting at 7 to 5 Ma coincide (Fig. 10) with the timing of a documented regional compressive phase (Burris et al., 1987). Intraplate stresses are particularly effective for inducing large vertical differential motions at young passive margins, because of their lower flexural rigidity. This is consistent with and may explain the large-magnitude 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) and Embry (1988) have shown that a significant number of Jurassic unconformities are confined to the flanks of the North Sea basins and the Sverdrup Basin, respectively. 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 1. 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 intraplate compressional stresses or, equivalently, by relaxation of a tensional stress regime. As noted by Miller et al. (1987), the frequently observed correlation between unconformities on the shelf and in the deeper parts of continental margin basins might simply result from subaerial 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." It seems that the essential factor controlling the intrabasinal 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.
Figure 8. Documented stratigraphy Gulf de Lions passive margin (northwest 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).
Figure 9. Modeled stratigraphy of the Gulf de Lions passive margin for an elastic rheology of the lithosphere, adopting a strong compressive phase starting at the 5 to 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.

Figure 10. The paleostress field inferred from the stratigraphic modeling of the Gulf de Lions margin (Fig. 9) with timing of tectonic phases (after Burrus et al.,...
The stratigraphic modeling of the U.S. east coast and Gulf de Lions passive margins described in this paper and similar modeling for the North Sea (Kooi et al., 1988; see also Lambeck et al., 1987), strongly suggest that tectonics might be the controlling factor underlying the apparent sea-level record, even during glacial periods.

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 punctuated stratigraphy can be viewed as the natural consequence of short-term narrowing of basins due to moderate fluctuations in intraplate stress levels, superimposed on the long-term broadening of the basin due to thermal contraction. A paleostress field inferred from the U.S. Atlantic margin stratigraphy is characterized by a transition from overall tension during the Mesozoic to a more compressional regime during the Cenozoic. These findings are supported by 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 eustatic from tectonic controls on sea-level fluctuations. Stress-induced subsidence and uplift explains the observed record of vertical motions in the Gulf de Lions basin.

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