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Intraplate stresses and dynamical aspects of rifted basins

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ABSTRACT

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Intraplate stresses play an important role during the syn- and post-rift evolution of sedimentary basins. Deviations from long-term thermal patterns of post-rift subsidence as well as the development of unconformities within rifted basins reflect to a large extent the temporal fluctuations of the regional stress fields in the lithosphere. It appears that incorporation of intraplate stresses in dynamical models for basin development, together with a quantification of the role of petrological changes in the crust–lithosphere system, can explain some of the observed shortcomings of thermal models of post-rift basin subsidence. Late Neogene accelerations in tectonic subsidence in the deeper parts of rifted basins in the Northern Atlantic and Mediterranean regions could reflect a change in the level of intraplate stress over large areas of the globe. Non-thermal contributions to the subsidence record affect estimates of crustal extension and, consequently, influence the depth at which hydrocarbon source rocks enter the maturity window. Stress-induced changes in basement topography have also important consequences for the budget of fluid flow in the deeper parts of the sediment fill of the rifted basins as well as on the dynamics of diapirism.

Introduction

A common assumption in the analysis of rifted basins, invoked by the sometimes uncritical use of thermal models for basin formation, is that tectonic subsidence during the post-rift phase, is by its thermal nature, slow. One of the reasons for the popularity of the stretching model for basin formation (McKenzie, 1978) is its simple and elegant explanation for the succession of a rapid syn-rift phase of basin subsidence, followed by a long-term phase of subsidence caused by post-rift cooling and contraction of the lithosphere. Although in the stretching model stresses do play an important role during the formation of a rifted basin, the model assumes that at the end of syn-rift development, stresses in the lithosphere

reach a zero level. Furthermore, most of the current models for extensional basin formation are keyed to lithospheric strain due to an unknown and unspecified stress field rather than to the strain response of the lithosphere to a known and/or realistic stress state. Another reason why the relationship between lithospheric stress and strain in rifted basin modelling has not received full attention, is that until recently little was known about the actual stress state of the lithosphere.

Studies of the tectonic stress field within lithospheric plates have shown a causal relationship between processes affecting the plate boundaries and intraplate deformation. Stress-induced vertical motions of the order of a few kilometres in areas of intraplate large-scale folding in oceans and continents have been observed on long reflection seismic lines and SEASAT data (Stephenson and Cloetingh, 1991; Stein et al., 1989a, 1990), whereby the orientation of fold axes is in agreement with predictions of stress models which take

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Fig. 1. Compilation of observed maximum horizontal stress directions in the European platform (after Müller et al., 1992).

plate-tectonic forces acting on the lithosphere into consideration (Cloetingh and Wortel, 1985, 1986). Given that stresses of a magnitude close to the lithospheric strength are obviously capable to produce large magnitude vertical motions (up to several kilometres, e.g. in the northeastern Indian Ocean), it seems logical to expect more modest, though still detectable vertical motions if stresses are of a smaller magnitude than those observed in plates involved in collisional and rifting processes.

Available models of the post-rift evolution of intra-plate rifted sedimentary basins generally neglect, however, to address the effects of intraplate stresses. Only recently the first steps have been made in analyzing the consequences of the presence of intraplate stresses in the lithosphere on the development of post-rift basins.

This paper reviews the effects of intraplate stresses on subsidence and basin-fill of rifted basins and discusses their role in a variety of processes affecting the lithosphere of rifted basins. These processes, which include fluid flow, diapirism and metamorphism, have so far not yet been adequately addressed by thermal models.

Tectonic stresses in the plates

The present stress field within the lithospheric plates has been studied in great detail by the application of a wide range of observational techniques such as bore-hole break-outs, in-situ stress measurements, and earthquake focal mechanisms. Modern stress orientations show a remarkably consistent pattern, especially considering the heterogeneity of intraplate lithospheric structures, and indicate that stresses propagate from plate boundaries over large distances into the interior of the plates. The World Stress Map Project of the International Lithosphere Program has convincingly established the existence of large-scale, consistently oriented stress patterns within all lithospheric plates (Zoback and World Stress Map Team, 1989; Zoback, 1992). These observations indicate that regional stress fields are dominated by the effect of plate-tectonic forces acting on the lithosphere. Figure 1 presents the results of a recent compilation of stress direction data for the European part of the World Stress Map (Müller et al., 1992).

Stresses in the interiors of the plates affect the

Fig. 2. Schematic illustration of stress-induced subsidence/uplift at a rifted basin. (Below) The wedge of sediments, representing the basin, loads an elastic lithospheric plate and causes a flexural deflection of the lithosphere. (Above) Stress-induced differential deflection for tension and compression (after Cloetingh et al., 1985).

vertical motions of sedimentary basins (Cloetingh, 1988; Nemec, 1988; Ziegler, 1992a, this volume). An example of this is provided by the present stress field in the Northwest European platform where studies of borehole elongations in oil wells and of earthquake mechanisms have revealed a northwest oriented compressional stress field (Fig. 1) that appears to be dominated by effects related to the Europe/Africa collision and possibly also by ridge push forces originating at the seafloor spreading axis of the Atlantic Ocean (Zoback and World Stress Map Team, 1989). In Europe there is strong micro-tectonic evidence for repeated changes in the magnitudes and orientations of intraplate stress fields on a time scale of a few million years in association with collision and rifting processes (Philip, 1987; Letouzey, 1986; Bles et al., 1989; De Ruig et al., 1991). The study of palaeo-stress fields adds geological time as a parameter crucial to understanding the temporal fluctuations of intraplate stress fields.

Intraplate stresses and stratigraphy of rifted basins

Intraplate stresses modulate the long-term thermal subsidence of post-rift sedimentary basins (Cloetingh et al., 1985) and induce rapid differential vertical motions of a sign and magnitude that changes along the basin profile (Fig. 2). For example, for conventional sediment loading models (Watts et al., 1982; Cloetingh et al., 1985) a superimposed compressional stress state causes relative uplift of the basin flank, subsidence at the basin centre, and seaward migration of the shoreline; along the basin margin an unconformity develops that gives basinward way to an off-flapping sequence. Increases in the level of tensional stress induce widening of the basin, subsidence of the basin flanks, and thus cause landward migration of the shoreline and the development of a rapidly onlapping sedimentary sequence (Fig. 3a). Stress-induced vertical motions of the crust can also drastically influence sedimentation rates. For example, flank uplift, due to an increased level of compression (equivalent to relaxation of tension), can significantly enhance sedimentation rates and modify the infilling pat-

Fig. 3. Synthetic sedimentary fill of a 50 Ma old rifted margin, which is initiated by lithospheric stretching followed by thermal subsidence and flexural infilling of the resulting depression. Chronostratigraphic horizons are shown at 5 million year intervals. The lowermost unit denotes syn-rift sediments. From 30–35 Ma after rifting the level of tensional stresses increases to $3.3 \times 10^{12} \text{ Nm}^{-1}$ (1.4 kbar) and is subsequently relaxed back to zero stress (equivalent to an increase in compression) at 40 Ma after rifting. The sediment package bounded by the 30–35 Ma isochrons is shaded. Upper panel: predicted stratigraphy for conventional flexural sediment loading models (after Cloetingh et al., 1989a). Middle and lower panels: predicted stratigraphies for lithospheric necking models for necking depths of 15 and 30 km, respectively (after Kooi and Cloetingh, 1992).

tern, promoting the development of unconformities (e.g., Galloway, 1989). Similarly, pre-existing sub-basinal fractures/faults can be reactivated thus causing intrabasinal “noise” in the overall subsidence pattern (see Nemec, 1988).

Lithospheric necking and stress-induced changes in stratigraphy

As pointed out by Braun and Beaumont (1989), predictions of basin formation models will change for a non-zero strength lithosphere during rifting. The presence of a finite strength of the lithosphere during rifting implies that apart from sediment loading, a vertical load is exerted by intra-lithospheric loads. Kooi et al. (1992a) using ECORS data from the Gulf de Lions margin (amongst others) as a constraint, investigated the effect of the depth of the lithospheric necking on the vertical motions of rift shoulders which flank rifted basins. Necking at depths shallower than 15 km produces downward flexure of the rift basin and eliminates rift shoulder uplift. A deeper level of necking is associated with an upward state of flexure and promotes the development of steep shoulder uplift. The actual depth of necking reflects the interplay of stresses with lithospheric rheology and is important in the context of discussions on the role of simple shear versus pure shear mechanisms in the lithosphere (see also Ziegler, 1992a, this volume). Being closely related to temperature, the depth of the intra-crustal brittle-ductile transition will gradually shift upward during the evolution of a rift; as a result, the crustal necking level will in general also move upward during rifting, promoting the development of detachments at shallow levels in the crust.

As demonstrated by Kooi and Cloetingh (1992), subtle changes between stress-induced relative sea-level changes and their stratigraphic expression are predicted for necking models relative to the conventional sediment loading models (see Fig. 3b and c). However, differences between these models are particularly pronounced when the conventional flexural sediment loading model is compared with models for deep necking levels. It is expected that the implications of necking models are evident during the rifting stage of basin development when differences in the flexural system are at a maximum. During the post-rift evolution of the basin, predictions of necking models tend to converge with the stratigraphic patterns predicted by traditional flexural models.

In this context, it is interesting to note that the late-stage post-rift subsidence record of rifted basins around the Atlantic, discussed in the following section, is consistent with models involving shallow levels of lithospheric necking.

Roles of tectonics and eustasy in the Atlantic and the North Sea

A significant part of the Mesozoic sequence and megasequence boundaries of the sedimentary fill of rifted basins around the Atlantic and the Arctic oceans, is associated with large-scale, fault-controlled rifting activity, while Cenozoic sequence boundaries in the Arctic were mainly controlled by large-scale compressional activity and inversion tectonics (Hubbard, 1988; Ziegler, 1988). A similar simultaneous occurrence of high frequency faulting activity and an increased intensity in sea-level fluctuations has also been noted in the Early Jurassic stratigraphic record of the North Sea (Hallam, 1988).

Modelling of the stratigraphy of the U.S. Atlantic margin (Cloetingh et al., 1989a) and the North Sea (Kooi and Cloetingh, 1989a; Kooi et al., 1991) has shown that the architecture of these basins can be successfully simulated by a model in which a stress field, whose magnitude fluctuates through time, is superimposed on the long-term thermal subsidence model. The inferred palaeo-stress was found to be largely consistent with independent data sets on plate kinematics (Klitgord and Schouten, 1986) and the tectonic evolution of the respective areas (Letouzey, 1986; Ziegler, 1989; Ziegler and Van Hoorn, 1989). For instance, the northern/central Atlantic area was dominated during Mesozoic times by a tensional stress field that was followed during the Tertiary by a compressional stress field whose magnitude increased with time.

Analysis of the stratigraphy of the Canadian Atlantic margin (Cloetingh et al., 1989b) has shown that the bulk of Mesozoic sequence boundaries can be correlated with stress changes which occurred during rifting in the north/central Atlantic. The tectonic and structural evolution of the eastern Canadian continental margin supports tectonic linkage between continental crust

and oceanic crust. This linkage is reflected in the extensional subsidence history of the Mesozoic basins which underly the Grand Banks and in the timing and pattern of seafloor spreading. On a large scale, syn-rift and post-rift sedimentary sequences are separated by sequence boundaries, often corresponding to unconformities. On a smaller scale, local unconformities and regional stratigraphic markers indicate adjustment to intermittent subsidence. Intermittent periods of increased tensional stress, associated with rift episodes in the northern and central Atlantic, and subsequent rapid relaxation of these stresses explain the Vail et al. (1977) coastal onlap-offlap charts. Both timing and nature of Vail's second-order and third-order cycles appear to reflect to a large extent the plate tectonic evolution and associated changes in stress regimes of the northern and central Atlantic.

The study of Mesozoic and Tertiary rifted basins on the Iberian plate provides further examples of rapid deviations in the subsidence record that seem to be governed by far-field stresses related to plate-interaction. For example, onset of the Pyrenean collision is recorded by steepening of slopes of rifted basins in the Betics and associated destruction of carbonate platforms (De Ruig et al., 1991). Far-field stress transmission is substantiated by palaeo-stress measurements, while the observed wavelength of basin deflection is consistent with predictions from numerical models.

Plate-interactions and stress-induced sea-level change versus global eustasy

Sequence stratigraphy has had a major impact on the interpretation of the sedimentary record of basins from seismic data and therefore on the understanding of the evolution of rifted basins. Sea-level changes have been shown to correlate with changes in calcite compensation depth, oxygen and carbon isotope composition, faunal productivity and distribution, silica diagenesis, climate, deep oceanic circulation, seismic reflectors in carbonate series and preservation of organic carbon (Watkins, 1989). It is, however, often not clear whether these processes are the direct re-

sult of eustatic sea-level changes or are caused by tectonic processes inducing fluctuations in relative sea level.

The preference of Vail et al. (1977) for an interpretation of the short-term (1–5 Ma) cycles in sea-level changes in terms of a glacio-eustatic mechanism was partly based on the inferred global character of the sea-level cycles; this issue has caused major debate (e.g. Miall, 1986; Hubbard, 1988). Vail's cycles, although based on data from different basins around the world, are heavily weighted in favour of the North Sea and the northern/central Atlantic margins, which is important as this obviously strongly affects views on the causes of short-term changes in sea level (e.g. Sloss, 1991; Aubry, 1991). As pointed out by Pitman and Golovchenko (1983) and Kominz (1984), variations in seafloor spreading rates, hot spot activity and orogeny fail to produce sea-level changes at the rate of third-order cycles, because these tectonic mechanisms are associated with a long thermal inertia of several tens of million years. Glacio-eustasy, operating during, for example, Permo-Triassic and Late Cenozoic times, can easily induce both the rate and magnitude of the inferred sea-level changes. Although the globe has been only during very short geological periods truly ice-free (Ziegler, 1990), glacio-eustasy fails to explain the occurrence of third-order sea-level cycles during Jurassic, Cretaceous and Palaeogene times where geological evidence for low altitude glaciation is lacking. The latter time slice corresponds to the final stages of the break-up of Pangea during which a large part of the rifted continental margins were formed, suggesting that tectonic factors played a dominating role. Furthermore, glacio-eustasy is unable to cause uniform lowerings and rises of sea level as models of post-glacial rebound have shown; the sign and magnitude of the induced sea-level change is dependent on the distance from the ice cap (e.g. Lambeck et al., 1987). One should, therefore, carefully distinguish between local effects related to ice-loading and global, eustatic effects of storing large volumes of water on continental lithosphere.

As discussed above, short-term changes in relative sea level can equally well be caused by

rapid, stress-induced vertical motions of the lithosphere (see Cloetingh, 1986). Hence, it appears that stresses, apart from being important in the development of rifts, also play a critical role during the subsequent post-rift subsidence of such basins. Undoubtedly, both eustasy and tectonics have contributed to the record of short-term changes in sea level. As the relative contribution of both mechanisms varies in magnitude, the development of stratigraphic criteria differentiating between tectonically and eustatically induced sea-level fluctuations is vital. As pointed out by Nemec (1988) and Embry (1990) such studies should be carried out both on an interbasinal and an intrabasinal scale. Embry and coworkers (Embry, 1990; Mørk et al., 1989) recognized a number of diagnostic features in the stratigraphic record of rifted basins supporting a tectonic control of their subsidence. These criteria include sediment source areas and sedimentary regimes varying from one sequence to the next, faults that terminate at sequence boundaries and significant changes in intrabasinal subsidence and uplift patterns as well as the absence of sequence boundaries in parts of the basins.

Whereas deviations from global patterns are a natural feature of the intraplate stress model, the

occurrence of short-term deviations does not preclude the occurrence of global events of tectonic origin which are reflected in the stratigraphic record. Such events are to be expected during periods of major plate reorganizations causing simultaneous changes in the tectonic stress fields in more than one plate, in response to their interaction (e.g., Pollitz, 1988; Ziegler, 1992b, this volume) and also during times prior to and shortly after Triassic–Middle Jurassic break-up of Pangea where continents and rift basins were in a largely uniform stress regime (Dewey, 1988; Ziegler, 1992b, this volume). The magnitude of the stress-induced rapid uplift and subsidence varies across the basin profile; this provides another important criterion for separating stress-induced relative sea-level changes from eustatic effects. Moreover, differences in rheological structure of the lithosphere caused, for example, by rift-induced attenuation of the continental lithosphere, affect the magnitude of the stress-induced vertical motions.

Non-thermal contributions to the subsidence record

The McKenzie (1978) model of basin formation predicts a syn-rift rapid phase of initial subsi-

Fig. 4. Location map showing areas in the Northern Atlantic and Mediterranean with distinct phases of rapid acceleration in tectonic subsidence during late Neogene times. CNS, MNM, CM, USM, GL, LM, indicate the Central North Sea, Mid Norway margin, Eastern Canadian margin, Eastern U.S. margin, Gulf de Lions, and the Levant margin, respectively.

Fig. 5. Deviations from thermal patterns of subsidence observed for a number of rifted basins in the Atlantic/Mediterranean region. (a) U.S. Atlantic margin (after Heller et al., 1982). (b) Eastern margin of Canada (after Cloetingh et al., 1990; Kooi, 1991). (c) Mid Norway margin (after Pedersen and Skogseid, 1989). (d) North Sea basin (after Kooi et al., 1991). (e) Gulf de Lions margin (after Burrus et al., 1987). (f) Levant margin (after Tibor et al., 1992).

dence followed by long-term post-rift subsidence that is governed by cooling of the lithosphere. Lithospheric stretching occurs in response to far-field stresses (passive rifting). At the end of the rifting cycle these stresses are assumed to relax. An essential assumption of the model is, therefore, that stresses are zero after formation of the rift basin. The original lithospheric stretching formulation was a strictly kinematic one. Studies on the dynamics of lithospheric stretching have demonstrated that tensional stresses of the order of several kilobars are required to stretch continental lithosphere (Cloetingh and Nieuwland, 1984; Sawyer, 1985a). In this respect, theoretical advances in lithospheric rheology, based on extrapolation of rock mechanics data have made an important contribution (Carter and Tsenn, 1987).

After an initial event of rift-induced basin formation, subsequent phases of rapid basin subsidence, which cannot be attributed to changes in sea level, are frequently explained in terms of multiple stretching phases (e.g. Greenlee et al., 1988). However, it must be realized that an increase in compressional stresses can also cause rapid basin subsidence and thus deviations from the subsidence patterns predicted by thermal models of basin subsidence (Kooi and Cloetingh, 1989b; Cloetingh et al., 1990). Phases of lithospheric compression during the post-rift evolution of rifted basins can give rise to substantial deepening of the basin centre, accompanied by uplift at basin flanks. The effect of such late-stage compressional phases is enhanced by brittle-ductile rheologies implying a finite strength of the lithosphere, particularly when stress levels approach the lithospheric strength.

Stresses and the Late Neogene acceleration in subsidence of post-rift basins

In the Atlantic–Mediterranean region growing evidence is accumulating for Late Neogene particularly strong deviations from the subsidence patterns predicted by thermal models for rifted basins. Figure 4 gives the location of some of the basins where recent studies demonstrate an acceleration in tectonic subsidence during the Plio-Pleistocene; for each of these basins a back-

stripped subsidence curve is given in Fig. 5. As shown by Cloetingh et al. (1990), late-stage compression can explain the rapid phases of Late Neogene subsidence of the North Atlantic passive margins and palaeo-rifts. A prominent reorganization of spreading directions and rates occurred at 2.5 Ma along the entire Atlantic seafloor spreading axes (Klitgord and Schouten, 1986). Important tectonic phases during Late Neogene times also occurred on the western side of the Atlantic Ocean. A climax in compressional tectonics in the Arctic of northern Alaska and northern Canada occurred at about 6 Ma and is possibly connected with the development of an incipient convergent plate boundary (Hubbard et al., 1987). Similarly, the decrease of extension in the southern Basin-and-Range province during Pliocene times coincides with important changes in the basin evolution in the Gulf of Mexico (Galloway, 1989). Episodicity in plate motions and associated changes in the Pacific and Atlantic plates in the late Miocene (9 Ma) and Pliocene (4 Ma) have recently been documented in great detail by Pollitz (1988). His analysis provides strong evidence of mechanical coupling between the plates by showing, for example, that changes in the relative motion of the Pacific and Northern American plates are related to plate driving forces originating in the northwestern Pacific subduction zones.

Does the Late Neogene record reflect a global plate interaction?

In the Late Neogene record of the Atlantic–Mediterranean region, the simultaneous occurrence of environmental changes, including the onset of glaciation and the well-known Messinian dessication effect, and the ongoing tectonic activity, expressed in the subsidence curves given in Fig. 5, are of particular interest. The key question that arises is whether a causal correlation or amplification effect exists between these factors. It is strongly suggested that the sediments in the rifted basins around the Atlantic record a phase of intensive global compressional tectonics, that is associated with an important Late Neogene plate reorganization of possibly global nature

(Cloetingh et al., 1990). These findings are also interesting in view of the partly overlapping occurrence of tectonic activity and glaciation in Quaternary times. The Late Neogene onset of the acceleration in basin subsidence in the Atlantic occurs well before the first occurrence of glaciation (1.6–1.9 Ma). This observation and the differential character of the uplift and subsidence at different positions within rifted basins around the North Atlantic, rules out glaciation as the main cause for the Late Neogene subsidence phases.

On the other hand, it is well known that periods of increased elevations promote the development of glaciation (e.g. Powell and Veevers, 1987). Although uplift in its own is only part of the dynamics of glaciation and changes in the air circulation patterns (Ruddiman and Raymo, 1988), the close relationship between glaciations and regional uplift seems to be more than coincidental. Plio-Pleistocene stress-induced downflexing in the central North Sea basin appears to be associated with an uplift of the Fennoscandian shield and the British Isles (Cloetingh et al., 1990; Ziegler, 1990; Kooi et al., 1991). Therefore, a causal link (Fig. 6) could exist between the build-up of compressional stresses during Late Neogene time, inferred from the modelling of subsidence and stratigraphy of rifted margins around the North Atlantic, and the onset of glaciation during Quaternary time.

We feel that an explanation for the observed rapid Late Neogene accelerations in subsidence of the North Sea Basin and the Atlantic shelves (Heller et al., 1982; Nielsen et al., 1986) in terms of an increased level of intraplate compression is more likely than invoking a renewed phase of crustal stretching, for which there is no evidence in these basins (see Fig. 1).

The Barents Sea (Cloetingh et al., 1992a) as well as the Mid-Norway margin (Pedersen and Skogseid, 1989) also show clear evidence for accelerated subsidence during the Late Neogene. Mapping of the horizons marking the base of the Tertiary on profiles running perpendicular to the Norwegian continental margin gives evidence for a flexural shape of the Neogene lithospheric deflection, whereby subsidence of the shelf is cou-

COMPRESSION-INDUCED DOWNWARDING

Fig. 6. Cartoon illustrating the spatial relationship between stress-induced downbending resulting in an acceleration in late Neogene subsidence in the Central North Sea and stress-induced uplift of the British Isles and onshore Norway.

pled with uplift of the onshore areas and erosional truncation of the strata in the coastal areas (Doré, 1992). The wavelength of the observed deflection is consistent with flexure induced by sediment loading, while the observed amplitude of the vertical deflection points to an amplification of the deflection induced by sediment loading by intraplate compression (Cloetingh et al., 1990). The present day stress field off the Norwegian margin has been investigated using bore-hole break-out techniques (Spann et al., 1991) and is characterized by a maximum horizontal compressional stress axis oriented roughly perpendicular to the margin.

Both the Northern Atlantic and the Arctic regions have been the site of a relatively high level of tectonic activity during Late Cenozoic times. Recent studies of neotectonics and seismicity (see Stein et al., 1989b) demonstrate a high level of intraplate deformation for the Norwegian "passive" continental margin. Unloading of the Fennoscandia ice sheet and associated glacial erosion provide an important contribution to the vertical motions in the Barents Sea and Norwegian margin. However, the observed thickness of

offshore Plio-Quaternary sedimentary wedges and the magnitude of the inferred coastal uplift and basin margin erosion (Cloetingh et al., 1990) cannot be explained by glacial erosion as its characteristic magnitude is of the order of only a few hundred metres (Stein et al., 1989b) and requires a contribution from another mechanism. Thus it seems that uplift-induced glaciation is not only restricted to orogenic belts (e.g. Himalayan and Rocky Mountain plateau) but can also occur in cratonic areas such as along the northern Atlantic margins. The simultaneous occurrence of glacial unloading and tectonically enhanced uplift of Scandinavia would imply that current estimates of ice thickness, ignoring a tectonic component to the uplift, and based only on the study of its postglacial rebound uplift history, are too high.

The synchronicity of the observed deviations of subsidence patterns from those predicted by thermal models of basin evolution suggests that stresses were exerted on the North-Atlantic area in conjunction with collisional tectonics in the Alpine-Mediterranean domain. The study of late Cretaceous and Cenozoic compressional foreland deformations in western and central Europe indicate that compressional stresses were intermittently exerted on the foreland of the Alpine orogen (Ziegler, 1987, 1990). However, also in the Mediterranean Basin examples of accelerated Late Neogene subsidence can be found, for instance in the Gulf de Lions rifted margin and the eastern Mediterranean Levant margin. The uppermost Miocene to recent subsidence record of the Gulf de Lions deviates strongly from the prediction of the McKenzie (1978) model and geologic evidence is lacking for a phase of renewed stretching (Burrus et al., 1987). While in the Gulf de Lions margin, the cause of the acceleration in subsidence cannot be directly related to large scale deformation, a similar acceleration in the Levant margin (Tibor et al., 1992), coincides with a peak in compressional tectonics and the uplift of the Judea mountains. Synchronous changes in Pliocene stress field of the Mediterranean and northwestern Europe have been documented (Philip, 1987) and are associated with the occurrence of discrete stratigraphic events (Meulenkamp and Hilgen, 1986). It appears,

therefore, that changes in the convergence of the African and Eurasian plates, also imaged by seismic tomography (Spakman, 1990; De Jonge and Wortel, 1990), are expressed in the forelands of the Alpine orogen.

Rapid vertical motions in rifted basins at a time long after they have become tectonically inactive have also been documented outside the Northern Atlantic/Mediterranean region. For example, rapid uplift has occurred in Late Neogene times along the rifted margins in the southern Atlantic, leading to pronounced topography at the Brazilian margin (Chang et al., 1992) and segments of the African margin. These distortions in the patterns of decreasing thermal subsidence can be correlated with documented changes in the geometry and spreading rates of the Equatorial and South Atlantic Ridge during the last 10 Ma (Brozena, 1986). Moreover, in the Indian Ocean, the development of Late Neogene unconformities and abrupt changes in subsidence have also been documented for the Northwestern Australian margin (Cloetingh et al., 1992b). Similar changes in the stratigraphic record of vertical motions, are also observed on the Western margin of India (Whiting, 1991), and coincide with the onset of intraplate deformation that has caused the folding in the northeastern Indian Ocean (Stein et al., 1989a, 1990).

Implications

Intraplate compressional stresses, apart from causing lithospheric deflections, may have a bearing on fluid flow, metamorphism, diapirism and crustal thickening.

Stress-effects on fluid flow in rifted basins

Fluid flow plays an important role in the evolution of rifted basins (Ungerer et al., 1990), and is probably related to the thermo-mechanical control exerted by the lithosphere on the evolution of such basins. Stress-induced changes in basement topography are insofar important as they cause a change in the fluid pressures in sedimentary basins. Numerical studies demonstrate that the stress-induced vertical motions can

effectively change the dynamics and interplay of compaction driven and meteoric fluid flow (Van Balen and Cloetingh, 1992). It should be noted that previous work (Bethke et al., 1988) has demonstrated the impact of eustatic falls in sea level on overall dynamics of fluid flow. Van Balen and Cloetingh (1992) have shown that relative changes in sea level, caused by intraplate stresses, provide an interesting alternative explanation for such phenomena. Stress-induced flank uplift and subsidence of the central parts of a rifted basin may lead to an increase in meteoric water influx and compactional driven flow, respectively. Consequently, the total fluid flow in a basin is intensified as a consequence of the build-up of intraplate compressional stresses; this affects the interaction of meteoric and compaction driven fluids (Fig. 7). Fluid flow in sedimentary basins is primarily concentrated in permeable units and

consequently is essentially in a lateral direction. However, stress-induced deformation of a basin may be accompanied by folding and faulting of its sedimentary fill (e.g. Stein et al., 1990); this can lead to changes in the localised fluid flow paths. Faulting (Etheridge et al., 1991), as well as fracturation of reservoirs and seal rock can be expected, with important consequences for hydrocarbon migration and sediment diagenesis. Furthermore, rapid stress-induced subsidence perturbations could provide an explanation for the development of overpressures as well as rapid dewatering of rift basins (e.g. Cathles, 1991). The contribution of stress to the record of fluid flow can be separated from the effects of eustatic sea-level fluctuations by exploiting the differential aspects of stress-induced subsidence from the uniform changes predicted by eustasy.

The effect of stress on fluid flow is not neces-

Fig. 7. Cartoon illustrating effect of compressional stress on fluid flow. (a) Interplay of meteoric water penetration from the basin flank and compaction driven fluids in a rifted basin in the absence of intraplate stresses. The length of the arrows provides a measure for the velocities of fluid flow. (b) Effect of compression induced flank uplift and increased subsidence and sedimentation in the basin centre on the fluid flow regime leading to pronounced changes in velocities and directions of flow (after Van Balen and Cloetingh, 1992).

sarily restricted to the sedimentary fill of basins. For example, in the area of intraplate deformation in the northeastern Indian Ocean stress-induced changes in fluid flow in the Bengal Fan and underlying oceanic crust could be responsible for the observed anomalously high heat flow. Recent data from ODP Leg 116 drilling indicate vigorous water flux through the sedimentary column and perhaps through the upper crust; this mechanism is compatible with the inferred shallowness of the heat source and intraplate seismicity to depths of about 30 km, which indicate that the lithosphere, as a whole, has not been significantly reheated by an upper mantle source (Stein et al., 1990).

Intraplate-stress and metamorphism

Deep seismic reflection studies (e.g. Pinet and Bois, 1990), as well as subsidence analysis (Moretti and Pinet, 1987; Ziegler, 1990; Kooi, 1991), have demonstrated the inability of the stretching model to fully explain the observed subsidence history of a large number of rifted basins (see also Ziegler, 1992b, this volume). Quantitative subsidence analyses of the Orphan Basin offshore East Newfoundland by Kooi (1991) demonstrated the need to invoke a post-formational increase in lithospheric density to produce the increase in long-term post-rift subsidence. Crustal metamorphism and phase changes are obvious candidates for the inferred crustal and lithospheric mantle density increase. A problem with the most popular mechanism, the gabbro–eclogite transition lies in the quantification of the effect (Artyushkov and Baer, 1990). A large number of unstable mineral reactions occur in the lower crust and upper mantle and it cannot be excluded that a modest perturbation in the stress field could contribute to such phase changes by crossing the threshold of the respective stability field. A likely mechanism would be provided by the effect of stress on diffusion rates of the phase change kinetics (Fowler and Nisbet, 1985), a phenomenon that is presumably analogous to the effect of differential stress on diffusion creep rates (Fig. 8).

Fig. 8. Schematic representation of possible effects of stress on crustal phase changes and associated subsidence.

Most estimates published for the rates of the gabbro–eclogite transition are for dry rocks; however, it is widely known that the presence of fluids can lead to much faster reaction rates. Therefore, it seems that stress-induced fluid flow in the crust underlying rift basins could provide a mechanism to enhance the effectiveness of phase changes. Moreover, in discussions on the depth at which this phase transition takes place, only the pressures exerted by vertical loads of the lithosphere are considered; however, also increasing horizontal stress levels in the lithosphere may contribute toward such phase changes resulting in a density increase of the lithosphere, thus promoting rapid subsidence of basinal areas. Apart from having implications for the interpretation of P – T – t studies, the possible effect of building-up intraplate compressional stresses, following relaxation of rift-related extensional stresses, might provide a productive avenue for further exploration and quantification of petrological contributions to post-rift basin subsidence.

Effects of intraplate stresses on estimates of crustal extension

As discussed above, stress-induced subsidence can contribute substantially to the total tectonic subsidence of post-rift basins. This is important because it is common practice to derive from total tectonic subsidence values of crustal extension (e.g., Sawyer, 1985b). Another independent estimate of extension can be obtained by measur-

ing horizontal displacements on normal faults active during extension. In general, a discrepancy exists between these two estimates of crustal stretching, (e.g., the North Sea basin; Sclater and Christie, 1980; Ziegler and Van Hoorn, 1989; Ziegler, 1992a, this volume). Late-stage compression can strongly contribute to the total tectonic subsidence (Fig. 9). Therefore, current backstripping techniques, correcting only for vertical loading of the lithosphere, tend to overestimate values of crustal extension and, by implication, of the thermal regime of the basin which has a bearing on the determination of the depth at which hydrocarbon source rocks enter the maturity window (Kooi and Cloetingh, 1989b). Stress-induced phases of short-term basin subsidence might intrinsically explain at least part of the discrepancies between the various estimates of crustal stretching obtained from subsidence analysis and structural interpretations.

Fig. 9. Effect of late stage compression on estimates of crustal thinning derived from subsidence analyses (after Kooi and Cloetingh, 1989b).

Stress and diapirism in rifted basins

Halites, often involved in diapiric structures, form an important aspect in the fill of many

Fig. 10. Cartoon illustrating effect of compressional stress on salt diapirism. The conceptual model illustrates the effects of superposition of flexural stresses induced by sediment loading and horizontal intraplate stresses induced by plate-tectonic forces. (Above) Zero intraplate stresses. (Below) An intraplate compressional stress regime of 100 MPa. Dashed line indicates the position of the neutral plane. The model illustrates the enhanced development of diapiric activity in a regime of intraplate compression (after Stephenson et al., 1992).

rifted basins (e.g. Jenyon, 1986; Ziegler, 1990). Current basins models, focusing on thermal aspects of basin evolution, do not provide a framework to incorporate salt diapirism in basin modelling schemes. A number of studies have demonstrated the inability of purely buoyancy driven diapirism as the prime mechanism for salt diapirism (e.g. Jenyon, 1986).

In the North Sea area, diapiric movements of the Zechstein salts commenced already during the Triassic, in part even after only a moderate thickness of overburden had accumulated (Ziegler, 1990). Some diapirs are associated with extensional basement faults, which presumably triggered their activity, while others evolved above unfaulted segments of their substrate. Diapirism in the North Sea Basin commenced during a clearly tensional phase of basin evolution (Hospers et al., 1988). Similarly, diapiric activity of Triassic–Early Jurassic salts of the Nova Scotia and Newfoundland shelves occurred during their Middle and Late Jurassic rifting stages, and of Carboniferous salts of the Barents Shelf during its Mesozoic rifting phases (see Ziegler, 1988; Tankard and Balkwill, 1989).

It, therefore, seems obvious that a rift regime, dominated by tensional stresses, promotes the development of salt diapirism. There are, however, also indications for an important role of compressional stresses in triggering diapiric activity during the post-rift evolution of rifted basins. Extensive field studies, as well as modelling of the evolution of the rift stratigraphy and tectonics (Stephenson et al., 1992), have revealed a close temporal relationship between the timing of changes in palaeo-stress and the timing of major diapir activity in the Canadian Sverdrup basin. In this basin, diapiric activity closely correlates with the Triassic–earliest Cretaceous and Palaeogene periods of compressional stress build-up inferred from basin analysis and modelling of its plate-tectonic evolution; in contrast diapiric activity is lacking during the Early to Middle Cretaceous time during which the area was dominated by a tensional stress regime (Stephenson et al., 1992). Such a relationship between mechanical factors and diapiric activity is of particular importance in the Sverdrup Basin, since the traditional buoy-

ancy mechanism fails to explain both the occurrence of anhydrite diapirs (density larger than the surrounding host rock) and the timing of their growth.

Stephenson et al. (1992) pointed out that the compressional intraplate stresses related to plate-tectonic forces and flexural bending of the crust by sediment loads (Cloetingh et al., 1982) can be an effective mechanism triggering diapirism (Fig. 10) even under conditions where the diapirs are intrinsically made up of high density material such as anhydrite. Modelling results of the Sverdrup Basin have also a bearing on the evolution of other rifted basins in the North Atlantic and Arctic which are characterized by diapiric activity in mid-Jurassic to mid-Cretaceous time (Jenyon, 1986). For instance, in the basins of the Canadian Grand Banks, after deposition of evaporites under a regime of overall tension, compressive flexural stresses develop in the basin centre, as a consequence of sediment loading of the syn-rift sedimentary sequences, while the superimposed intraplate stress regime set up by plate-tectonic forces also evolve from tension into compression (Ziegler, 1988), leading to an acceleration of diapiric growth during the post-rift subsidence phase of the basins. Numerical studies of diapirism (Zaleski and Julien, 1990) demonstrate the importance of the configuration of the rifted basins for the emplacement of diapirs. Steepening of the basement slope provides apparently an effective mechanism enhancing diapiric activity. Intraplate stresses, as discussed above are quite capable of distorting the basin shape, and, in the case of compression, causing steepening of the basin slopes, therefore, can play an important mechanical role in the development of salt tectonics which can modify the internal architecture of a rifted basin.

Conclusions

Sedimentary basins evolve in the interior of plates, the internal stress regime of which is subject to episodic changes mainly as a result of plate interaction. Recent work on intraplate tectonics has established a strong mechanical coupling between geodynamic processes at plate

boundaries and deformations in the plate interiors. The stratigraphic record of vertical motions in sedimentary basins holds the potential for unravelling the full complexity of the interplay between dynamic processes governing basin subsidence and the passive processes of sedimentation. Thermal models of basin formation, which do not address the mechanical aspects of basin evolution, intrinsically fail to predict the short-term deviations in basin geometry and subsidence rates. Analysis of the interplay between lithospheric stress regimes and long-wavelength deflections of the lithosphere holds the promise to establish an internally consistent and predictive formulation of the relationship between deep lithospheric processes governing the development of rifted basins and upper-crustal tectonics and the stratigraphic record preserved in the syn- and post-rift sedimentary fill of rifted basins. Careful analysis of the basin fill, recording the interplay of tectonics and changes in erosional base level, is required to separate effects of eustatic sea-level changes from stress-induced short-term motions of the lithosphere; both mechanisms cause similar short-term deviations from the long-term patterns of thermal subsidence. Similarly, effects of multiple stretching phases and repeated phases of increased levels of tectonic compression both give rise to rapid vertical motions of a magnitude that is well beyond the range covered by apparent sea-level changes. Much has yet to be learned from integrated analyses of the structural and stratigraphic evolution of rifted basins and the development of dynamic models for basin evolution. Quantification of the relative contributions of the different mechanisms towards long-term and short-term vertical motions in sedimentary basins may further our understanding of the mechanics of diapirism and fluid flow in rifted basins.

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