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Tectonics and global change – inferences from Late Cenozoic subsidence and uplift patterns in the Atlantic/ Mediterranean region

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SUMMARY

Quantitative subsidence analysis for a number of rifted basins in the northern Atlantic/Mediterranean region provides evidence for rapid phases of Plio-Quaternary subsidence. The observed acceleration in tectonic subsidence occurs after a phase of general quiescence in subsidence in these basins and deviates from predictions of stretching models. The latter indicate a decay of subsidence with time after Mesozoic–Tertiary basin formation and a slow tectonic subsidence in Plio-Quaternary times. A possible explanation for the observed patterns of anomalous subsidence could be an increase in the level of intraplate compression in the northern Atlantic region. Intraplate stress changes in the Plio-Quaternary are related to the dynamics of African/ Eurasian collision processes and a reorganization of spreading directions in the Atlantic, possibly reflecting a plate reorganization of global nature.

It seems that the Plio-Quaternary record reflects a period of increased levels of neotectonic activity, interplaying with periods of (de)glaciation. Stress-induced topography in the onshore parts of continental margins, coupled with the stress-induced subsidence in the offshore deeper parts of the basins, could have contributed to recent phases of uplift in Fennoscandia, augmenting the uplift induced by glacial unloading. Estimates of ice thicknesses are directly inferred from the observed uplift ignoring other driving mechanisms whereas topography plays a crucial role in the dynamics of glaciation. It is, therefore, important to quantify the interplay of rapid tectonic uplift and subsidence phases with climatic effects during the Plio-Quaternary.

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INTRODUCTION

Recent observations of stress orientations from earthquake focal mechanism studies, borehole elongations and *in situ* stress measurements (Zoback *et al.*, 1989; Zoback, 1992) have revealed the existence of consistently oriented stress fields in the lithosphere (Fig. 1), that are in close agreement with predictions of plate tectonic models (e.g. Cloetingh and Wortel, 1986; Wortel *et al.*, 1991). Studies of the palaeostress fields using structural geological techniques (Philip, 1987; De Ruig *et al.*, 1991) have expanded our insights into the temporal variations in stress fields by showing large changes in the observed patterns with geological time. The study of the stress regimes in the plates has demonstrated a close coupling between plate boundaries and plate interiors by stress propagation over large distances in the lithosphere.

Sedimentary basins located in plate interiors provide the time recorder of the processes acting on the lithosphere. Intensive seismic exploration and drilling (e.g. Tankard and Balkwill, 1989) as well as quantitative basin modelling (e.g. Angevine *et al.*, 1990) have made important contributions to our understanding of the basin formation processes and the basin fill (Kleinspehn and Paola, 1988; Price, 1989; Cross, 1990). Recent studies have shown that temporal changes in stress, occurring in association with changes in plate tectonic regime, could have a subtle but detectable effect on the record of vertical motions in sedimentary basins (Cloetingh *et al.*, 1985, 1989; Cloetingh, 1988) with rates well in excess of values associated with thermal processes in the lithosphere.

Rapid vertical motions and accelerations in tectonic subsidence have been observed in the late Cenozoic record of rifted basins in the Atlantic/Mediterranean region (Kooi *et al.*, 1989; Cloetingh *et al.*, 1990; Jensen and Schmidt, 1992; Burrus *et al.*, 1987; Horvath and Cloetingh, 1992). In the present paper we discuss implications of these observations in the light of a possible explanation associated with an increase in the level of compressional stresses in the plates. We begin with a review of mechanisms for basin subsidence pertinent to the observed record of vertical motions. Subsequently, we discuss the interplay of stress-induced changes in uplift and subsidence patterns with the dynamics of Plio-Quaternary (de)glaciation.

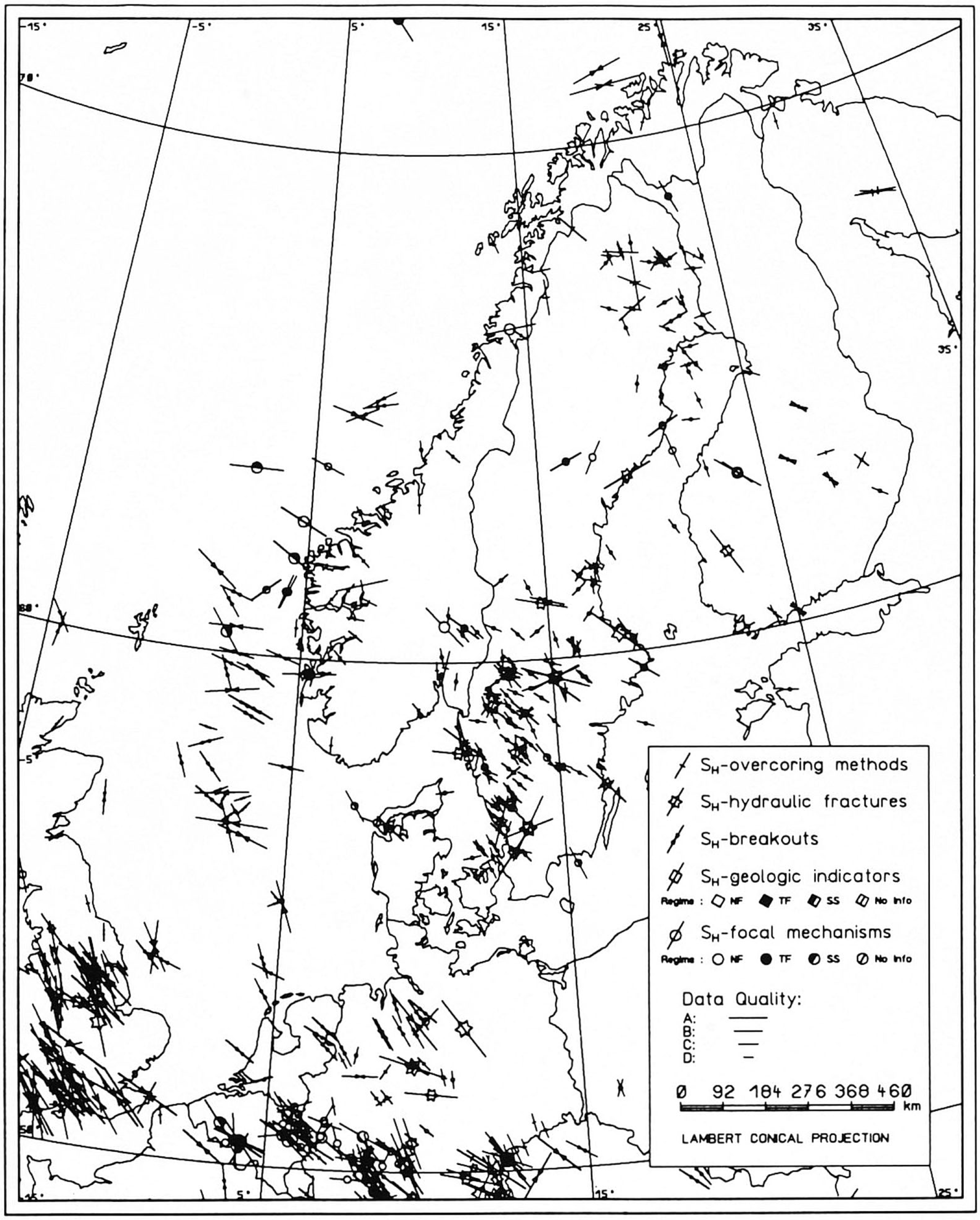

Fig. 1. *Compilation of observed maximum horizontal stress directions in the Northern Atlantic/Mediterranean region (After Mueller* et al., *1992).*

SUBSIDENCE OF RIFT BASINS AND TECTONICALLY INDUCED SEA-LEVEL CHANGES

The stretching model (McKenzie, 1978) is based on the assumption that post-rift basin subsidence results from thermal cooling of the lithosphere upon basin formation, amplified by the loading effect of sediments that fill in the basin. The predicted long-term decay in post-rift subsidence is intrinsically associated with the long thermal inertia of several tens of million years involved with the cooling of the lithosphere (Fig. 2). Lithospheric stretching occurs when tensional stresses in the lithosphere are of a level sufficiently high to induce rupture, whereas the model assumes that immediately after rifting has occurred stresses have been fully relaxed. However, as known from the study of the

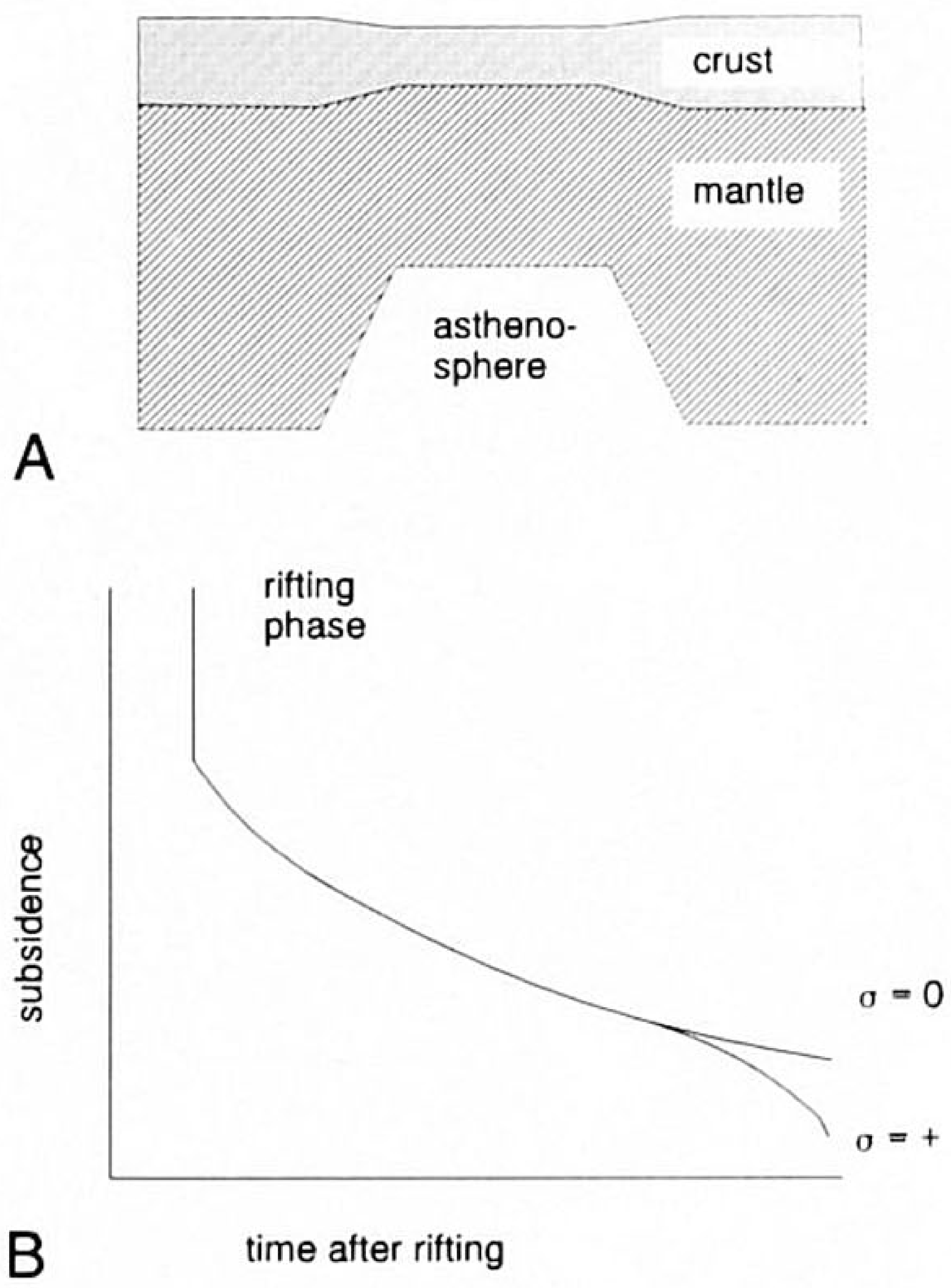

Fig. 2. *(a) The stretching model for the formation of rift basins (After McKenzie, 1978). (b) Predictions of subsidence by models of rift basins. Solid line: thermal subsidence; dashed line: deviation from thermal subsidence induced by an increase in the level of intraplate compression.*

present-day stress fields in the plates (Zoback, 1992), which demonstrates that the plate interiors are typically subject to a compressional regime, this assumption is essentially not correct.

Intraplate stresses modulate the post-rift thermal long-term basin subsidence (Cloetingh *et al.*, 1985) by inducing rapid differential vertical motions of a sign and magnitude that depends on position within the basin. For example, for conventional sediment loading models (Watts *et al.*, 1982; Cloetingh *et al.*, 1985) an increase in the level of compression leads to relative uplift of the basin flank, subsidence at the basin centre, seaward migration of the shoreline and the development of an offlap and an unconformity. Increases in the level of tensional stress induce widening of the basin, lowering of the flanks, and cause landward migration of the shoreline, producing a rapid onlap phase.

As discussed by Cloetingh (1991), rapid, stress-induced vertical motions of the lithosphere within sedimentary basins can contribute significantly to the record of short-term changes in relative sea-level. These tectonic components in the apparent sea-level record interfere with the glacio-eustatic signal. As is well-known (e.g. Pitman and Golovchenko, 1983), glacio-eustasy can easily induce both the rate and magnitude of the inferred sea-level changes but fails to explain the occurrence of short-term sea-level cycles during time intervals prior to the Late Cenozoic, when there is no geological evidence for low altitude glaciation. Glacio-eustatics is also unable to cause uniform lowerings and rises of sea-level as models of post-glacial rebound have shown that the sign and magnitude of the induced sea-level change is dependent on the distance to the location of the ice cap (e.g. Lambeck *et al.*, 1987; Lambeck, 1990).

Modelling of the stratigraphy of the US Atlantic continental margin (Cloetingh *et al.*, 1989) and the North Sea (Kooi and Cloetingh, 1989b; Kooi *et al.*, 1991) has shown that the punctuated stratigraphy of passive continental margins and rift basins can be successfully simulated by a basin model in which a stress field whose magnitude fluctuates through time is superimposed on the long-term thermal evolution of the lithosphere. The inferred palaeo-stress was found to be largely consistent with independent data sets on the kinematic (Klitgord and Schouten, 1986) and tectonic evolution (Ziegler, 1989) of the northern/central Atlantic, with a tensional stress field during Mesozoic times, followed during the Tertiary by a compressional stress field whose magnitude increases with time. Undoubtedly, both climate and tectonics have contributed to the record of short-term changes in sea-level (Haq *et al.*, 1987) with relative contributions of variable magnitude (Aubrey, 1991). Whereas deviations from global patterns are a natural feature of the intraplate stress model, the occurrence of short-term deviations does not preclude the presence of global events of tectonic origin elsewhere in the stratigraphic record. These are to be expected when major plate reorganizations in tectonic stress fields occur simultaneously in more than one plate due to plate interaction (e.g. Pollitz, 1988).

Tectonically induced vertical motions of the lithosphere can also drastically influence sedimentation rates because much of the sedimentary input to the basins is derived from the topographic areas flanking the basins. Stress-induced uplift (Fig. 3) can significantly enhance sedimentation rates and modify the patterns of infilling, leading to the development of unconformities during the post-rift phase (e.g. Galloway, 1989). Similarly, pre-existing sub-basinal fractures/faults can be reactivated to cause intra-basinal 'noise' in overall subsidence patterns (Nemec, 1988).

During basin formation, necking of the lithosphere can also lead to flank uplift. Examples include the Baikal rift, the Red Sea rift, the Jurassic–Cretaceous

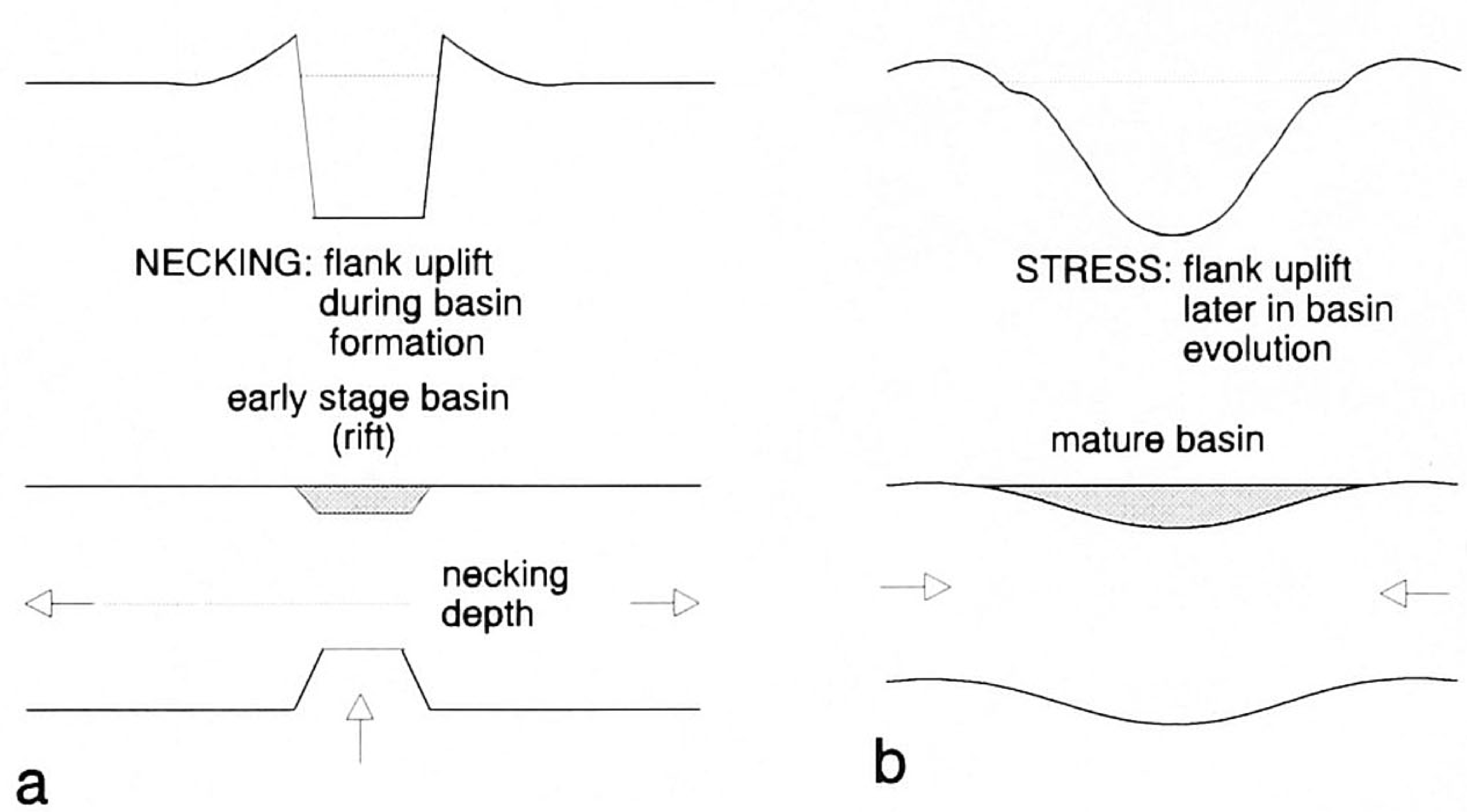

Fig. 3. *Two important tectonic mechanisms for the formation of rift shoulders flanking extensional sedimentary basins. (a) Flank uplift due to necking of the lithosphere during basin formation. (b) Flank uplift due to an increase in the level of intraplate compression during the post-formation stage of the basin evolution.*

North Sea Basin (e.g. Kooi *et al.*, 1992) and the Ross Sea embayment (Fitzgerald *et al.*, 1987). The possible occurrence of necking during the basin formation could also affect the patterns of stress-induced distortions in topography induced during the post-rift phase. As demonstrated by Kooi and Cloetingh (1992), subtle changes between stress-induced relative sea-level changes and their expression in the stratigraphy are predicted for different levels of necking. The differences are most pronounced when comparing the conventional flexural sediment loading model with models having deep levels of necking. The effects of necking will be greatest during the basin formation stage of rift basins where differences in the flexural system could be large. During the post-rift evolution of basins, predictions for models invoking necking converge to the stratigraphic patterns predicted by conventional flexural models. The late-stage subsidence record in rift basins around the Atlantic discussed in the following section is consistent with models involving shallow levels of necking.

Differences in rheological structure of the lithosphere (Carter and Tsenn, 1987) caused by, for example, the presence of weak attenuated continental lithosphere affect the magnitude of the stress-induced vertical motions. The Plio-Quaternary sedimentary record clearly has an important imprint by climate driven processes. At the same time, as will be discussed in the following section, a strong tectonic signal can be recognized in the Plio-Quaternary subsidence record.

THE PLIO-QUATERNARY SUBSIDENCE RECORD

Evidence is growing for particularly strong deviations from the subsidence patterns predicted by thermal models for rifted basins in the Atlantic–Mediterranean region in late Cenozoic times. Figure 4 gives the location of some of the basins where recent studies have demonstrated the occurrence of accelerations in tectonic subsidence. Figure 5 shows a panel with curves of tectonic subsidence of these basins obtained from quantitative subsidence analysis. Previous modelling studies (Cloetingh *et al.*, 1990; Kooi *et al.*, 1991) on the North Sea Basin have shown that maximum estimates of palaeobathymetry adopted from study of faunal assemblages cannot account for the observed subsidence, demonstrating the tectonic nature of the observed acceleration, with rates up to 0.1 cm y^{-1}. The acceleration in subsidence is expressed in up to 1 km-thick sedimentary Plio-Quaternary wedges documented by Cameron *et al.* (1987). As pointed out by these authors, some of the major faults in the southern North Sea Basin have been activated during Pleistocene times, leading locally to displacements of the base Quaternary by more than 100 m. The presence of thick Plio-Quaternary sediment wedges has also been demonstrated for the eastern Canadian continental margin (see Fig. 6). Inspection of Fig. 6 shows that an increase in the level of compression in Plio-Quaternary times can explain the presence of these sedimentary wedges as well as the rapid phases of late Cenozoic subsidence such as those encountered around the northern Atlantic.

A prominent reorganization of spreading directions and rates occurred 2.5 Ma along the entire Atlantic spreading centre (Klitgord and Schouten, 1986). Important tectonic phases during late Cenozoic 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 about 6 Ma, possibly connected with the formation of an incipient convergent plate boundary (Hubbard *et al.*, 1987). Similarly, the termination of extension in the 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 Upper Miocene (9 Ma) and Pliocene (4 Ma) have been documented in great detail by Pollitz (1988). His analysis provides strong evidence of a mechanical coupling between the plates by showing, for example, that the causes of the Pacific and northern American changes in plate motion are related to plate driving forces originating in the northwestern Pacific subduction zones.

An explanation for the rapid late

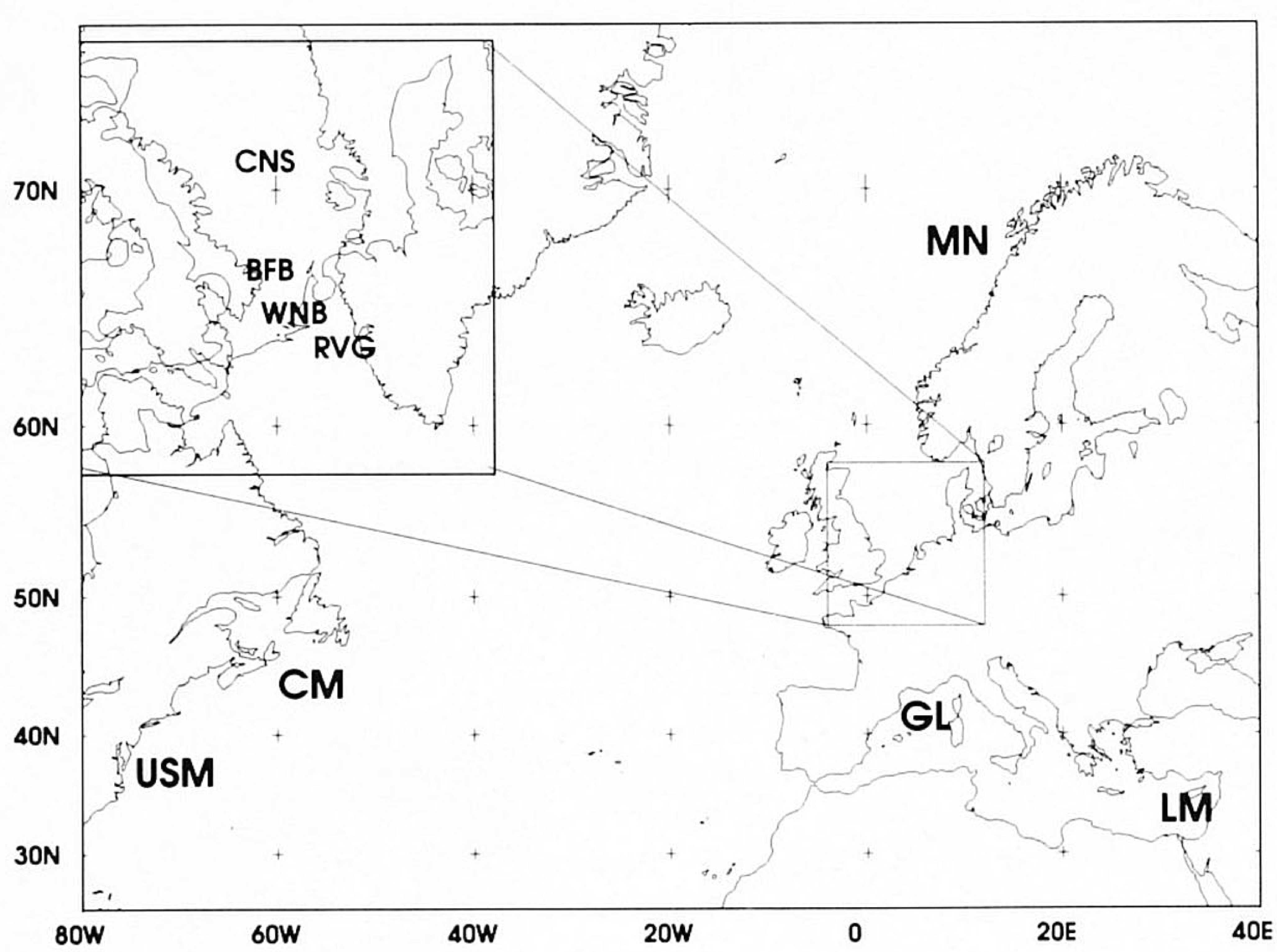

Fig. 4. *Location map showing areas in the Northern Atlantic and Mediterranean with distinct phases of rapid acceleration in tectonic subsidence during late Neogene times. CNS, BFB, WNB, RVG, MN, CM, USM, GL, LM, indicate the Central North Sea, Broad Fourteens Basin, West Netherlands Basin, Roer Valley Graben, Mid Norway margin, Eastern Canadian margin, Eastern US margin, Gulf de Lions, and the Levantine margin.*

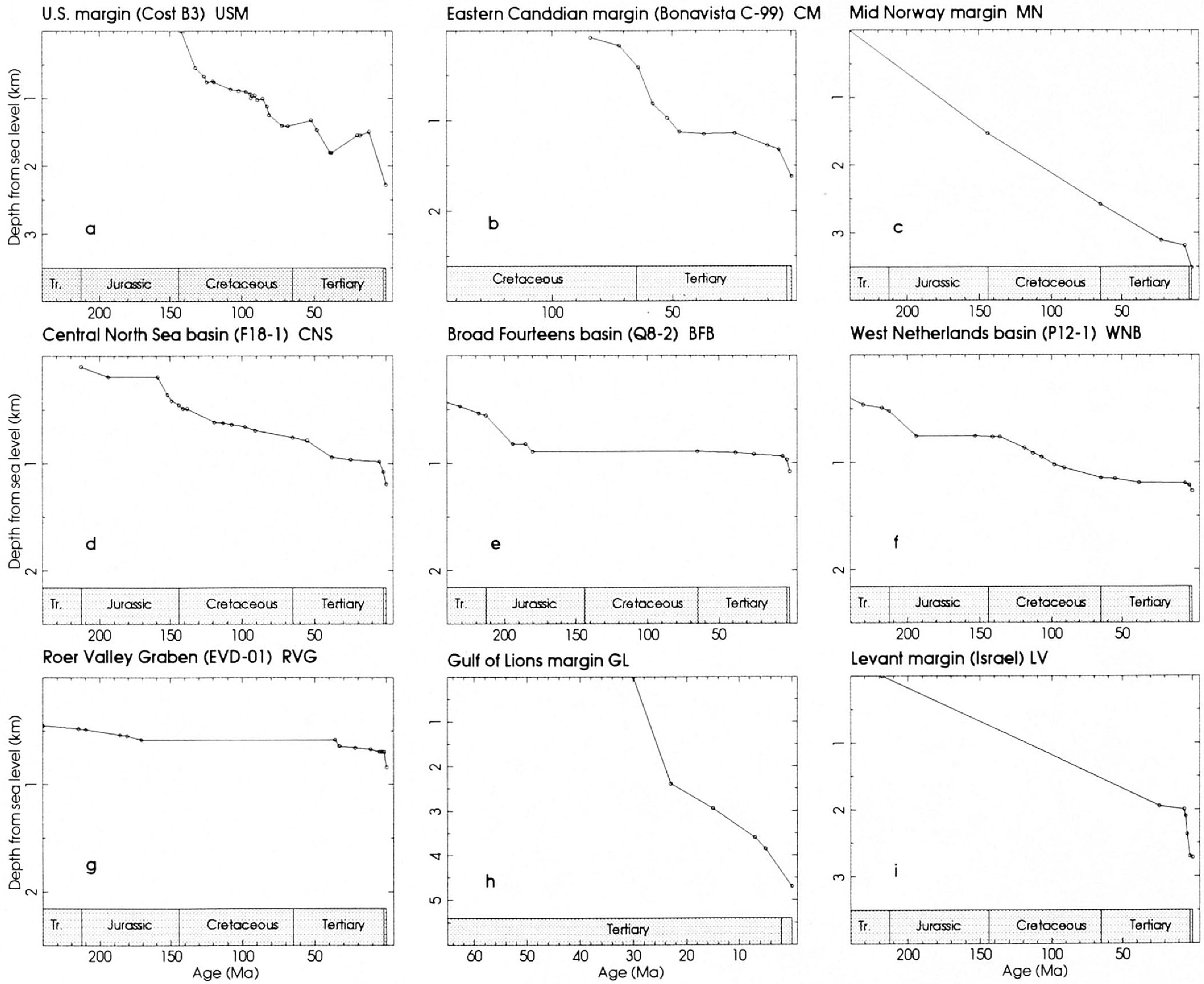

Fig. 5. *Deviations from thermal patterns of subsidence observed for a number of rift basins in the Atlantic/Mediterranean region. (a) Eastern US continental margin (After Heller* et al., *1982); (b) Eastern margin of Canada (After Cloetingh* et al., *1990; Kooi, 1991); (c) Mid Norway margin (After Pedersen and Skogseid, 1989); (d) South-central North Sea basin (After Kooi* et al., *1991); (e) Broad Fourteens Basin (After Kooi* et al., *1989); (f) West Netherlands Basin (After Kooi* et al., *1989); (g) Roer Valley Graben (After Zijerveld* et al., *1992); (h) Gulf de Lions margin (After Burus* et al., *1987); (i) Levantine margin (After Tibor* et al., *1992).*

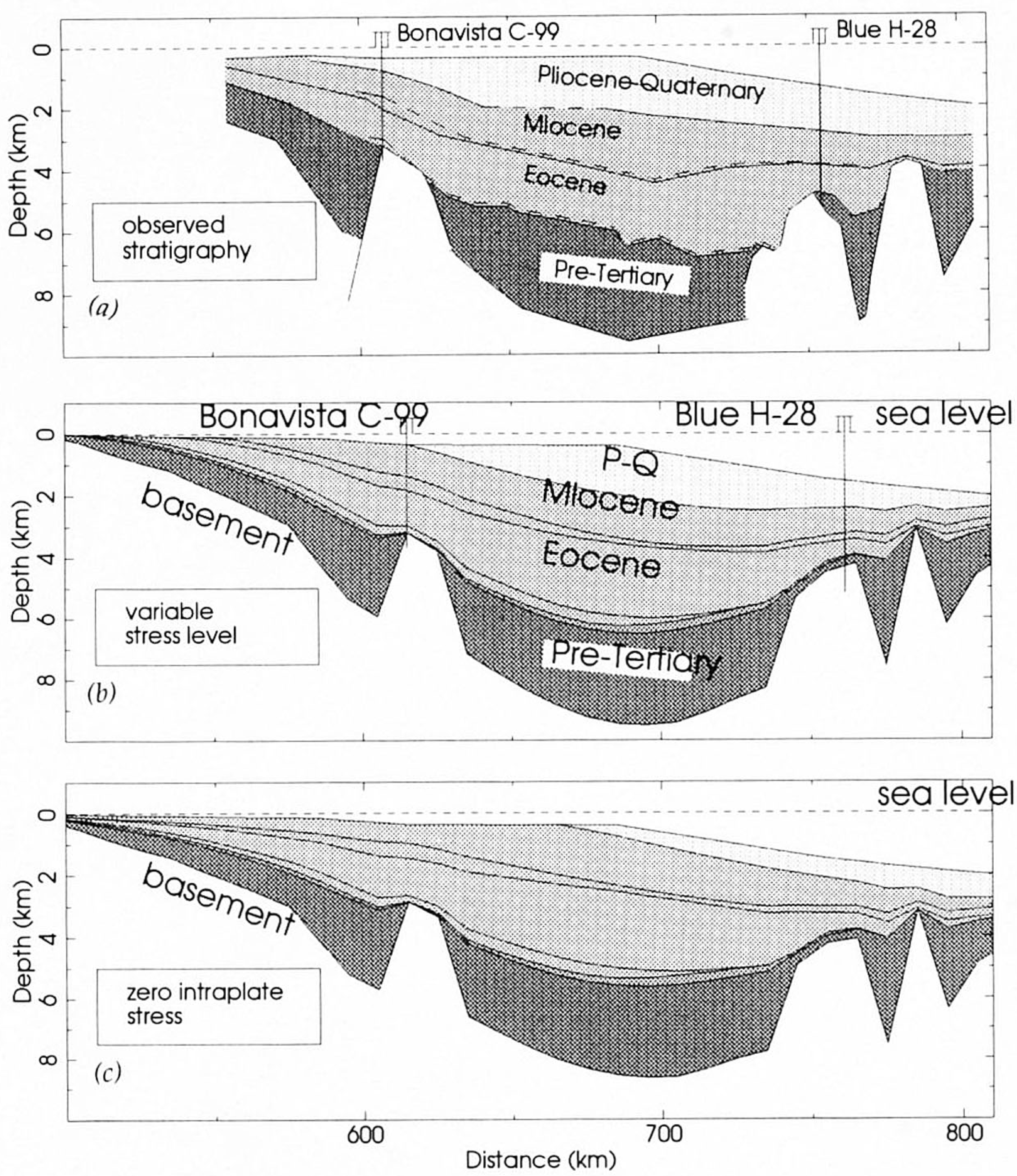

Fig. 6. *(a) Observed Canadian margin stratigraphy of the Orphan basin/Labrador shelf; (b) Modelled Canadian margin stratigraphy for a stretching model incorporating a Plio-Quaternary increase in compression; (c) Modelled stratigraphy adopting a stretching model and a zero level intraplate stress field.*

Cenozoic accelerations in basin subsidence in terms of an increased level of intraplate compression is more likely than a phase of renewed stretching, as the present-day stress field in NW Europe and the northern Atlantic is compressional in character (see Fig. 1). Measurements of the breakout orientations (Spann *et al.*, 1991) have elucidated the spatial distribution of the stress field in the North Sea/Norwegian margin displaying in the area of the Central North Sea Graben a bimodal stress distribution parallel and perpendicular to the main NW–SE trend of the European stress field (Mueller *et al.*, 1992). The stress observations in the Central Graben suggest that the variation in stress orientation is a consequence of the local structure of the Central Graben, resulting from the ratio of principal horizontal stresses and the contrasts in rheological properties between the graben and the surrounding lithosphere. Because the Central Graben strikes subparallel to the mean orientation of the western European stress field, the effect of stress rotation is larger in this region than in the Viking graben which strikes at a larger angle to the main trend of the far-field stress (Spann *et al.*, 1991).

The analysis of the subsidence record, and the coincidence in the timing of the observed deviations from predictions from thermal models of basin subsidence suggests the existence of a mechanical coupling between Mediterranean tectonics and the record in the Atlantic during late Cenozoic times. The existence of such a coupling in earlier time slices of the geological record of the Atlantic–Mediterranean region has also been demonstrated by the study of inverted basins (Ziegler, 1987), showing the far-field effects of Alpine collision tectonics in the basins of NW Europe. Quantitative subsidence analysis has demonstrated for a number of extensional basins in the Alpine/Mediterranean collision belt, including the Pannonian basin (Horvath and Cloetingh, 1992) and the Gulf de Lions rifted margin (Burrus *et al.*, 1987), patterns of anomalous rapid subsidence during the Plio-Quaternary. Particularly pronounced are the long wavelength subsidence/uplift anomalies, documented by Horvath and Cloetingh (1992), associated with large wavelength patterns of coupled subsidence in basin centres and uplifts at basin flanks during the late stage phase of the evolution of the Pannonian basin. The western Mediterranean Gulf de Lion rifted margin and the eastern Mediterranean southern Levant margin also form examples of a pronounced acceleration in late Cenozoic tectonic subsidence. As pointed out by Burrus *et al.* (1987), the uppermost Miocene to recent subsidence record of the Gulf de Lions deviates strongly from the prediction of the McKenzie (1978) model, while evidence is lacking for a phase of renewed stretching. While in the Gulf de Lions margin, the cause of the acceleration in subsidence is unclear, a similar acceleration in the southern Levant margin amplified by the load of the Nile delta (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 NW Europe have been documented (Philip, 1987) as well as the occurrence of discrete stratigraphic events (Meulenkamp and Hilgen, 1986).

A significant component of the record of recent vertical motions could, therefore, be caused by an increased level of compression reflecting an increased intensity in the coupling between the plates in some sectors of the Mediterranean collision zone. Such an enhanced level of compression is also consistent with observed steepening of basin slopes of some western Mediterranean basins (Mauffret *et al.*, 1981) and with seismic reflection data showing evidence for Pliocene–Quaternary inversion offshore Sicily (Milia, 1992). The increased plate interaction for these plate segments appears to go in concert with slab detachment inferred from tomographic images (Wortel and Spakman, 1992) in adjacent parts of the Mediterranean convergence zone. The latter areas include the eastern margin of Iberia, where quantitative modelling of the Valencia Trough (Janssen *et al.*, 1992) and Alboran Sea/Betics region (Cloetingh *et al.*, 1992c) has demonstrated the occurrence of a broad regional uplift during Late Neogene times.

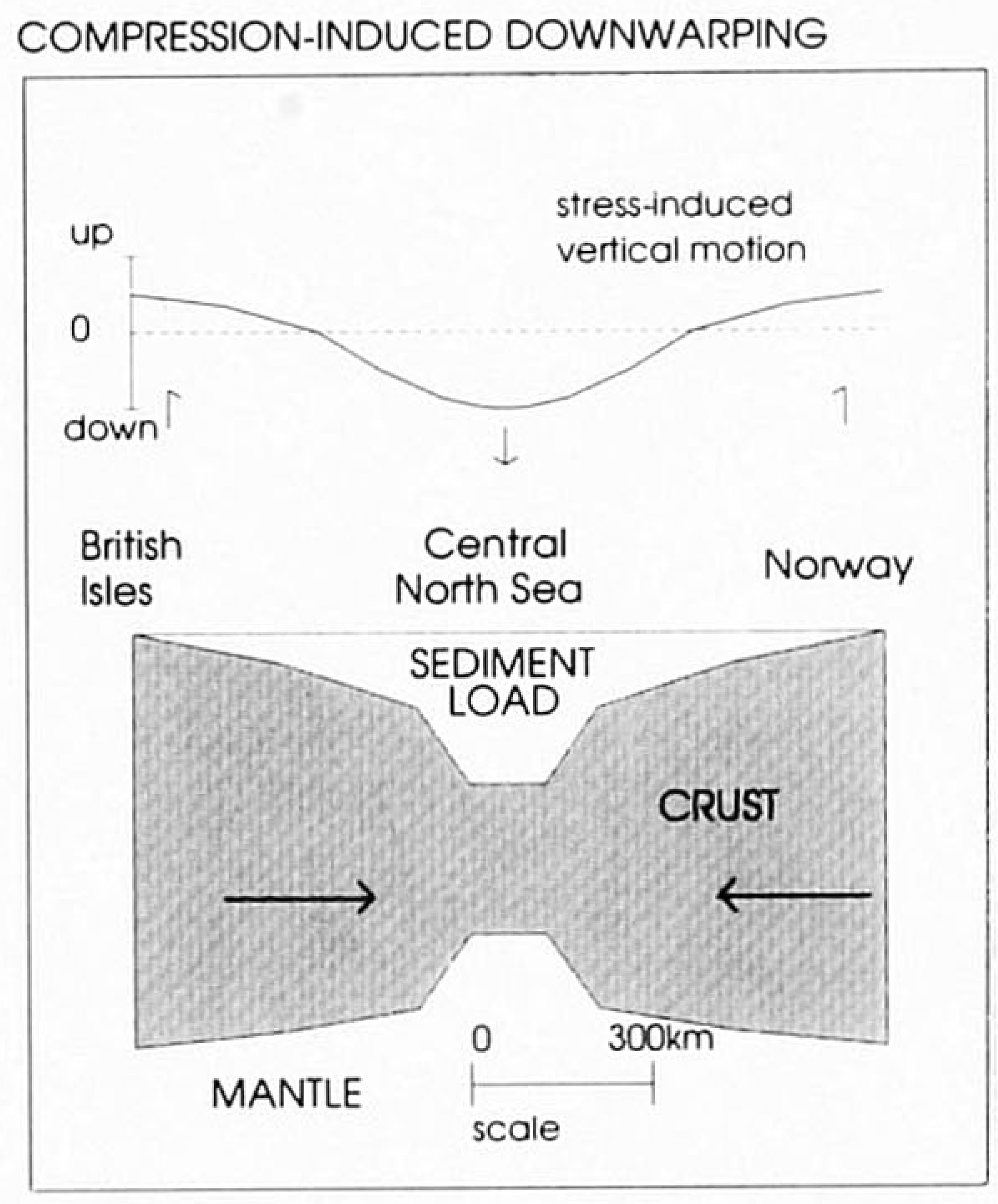

Fig. 7. *Cartoon illustrating the spatial relationship between stress-induced downbending resulting in an acceleration in late Neogene subsidence in the Central North Sea and stress-induced uplift of the British Isles and onshore Norway.*

Of particular interest are the simultaneous occurrence of environmental changes, of which the onset of glaciation is a prominent example, and the ongoing tectonic activity also expressed in the subsidence curves shown in Fig. 5. The key question that arises is whether a causal correlation or amplification effect exists between these factors. It could well be that the sediments of the rifted basins around the Atlantic record a phase of intensive global compressional tectonics, associated with an important late Cenozoic plate reorganization of possibly global nature. These findings are also interesting in view of the partly overlapping occurrence of tectonics and glaciation in Plio-Quaternary times.

TECTONICALLY-INDUCED UPLIFT: INTERPLAY WITH (DE)GLACIATION

The onset of the observed acceleration (Fig. 5) in tectonic subsidence in the deep parts of sedimentary basins occurs simultaneously with uplift in the onshore parts of the rifted continental margins and is well before the first glaciation (2–3 Ma). This observation and the differential character of the uplift and subsidence at different positions within the rifted basins around the northern Atlantic rules out glaciation as the main cause for the late Cenozoic 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; Raymo, 1991). 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 intimacy of glaciations and uplift seems to be more than casual. An interesting consequence (Fig. 7) of stress-induced downbending in the central North Sea could be an uplift of Norway and the British Isles (Cloetingh *et al.*, 1990; Ziegler, 1990; Kooi *et al.*, 1991). Apatite fission track analysis (Green *et al.*, 1992) has shown a broad regional warping producing kilometre-scale uplift and erosion of a wide area over much of the UK region. Green *et al.* showed evidence for a series of discrete uplift events throughout the Tertiary of which a large proportion occurred in the last 30 Myr up to the present day with wavelengths of a few hundred km over areas not restricted to local inversion axes. Similarly, most of the observed uplift of the Skagerrak area is of post-Mid Miocene age (Jensen and Schmidt, 1992).

A causal link (Fig. 8) could exist between the build-up of compression during late Cenozoic time inferred from the modelling of subsidence and stratigraphy of rifted margins around the northern Atlantic, and the onset of glaciation during Plio-Quaternary time. The Barents Sea (Cloetingh *et al.*, 1992a) as well as the Mid-Norway margin (Torudbakken and Gabrielsen, 1987; Pedersen and Skogseid, 1989) show clear evidence for an acceleration in late Neogene subsidence. Mapping of the Base Tertiary horizons for profiles perpendicular to the Norwegian continental margin has demonstrated a flexural shape for the lithospheric deflection, with a coupling of offshore subsidence and onshore uplift (Dore, 1992). The Base Quaternary reflector forms a major erosional unconformity in the north-

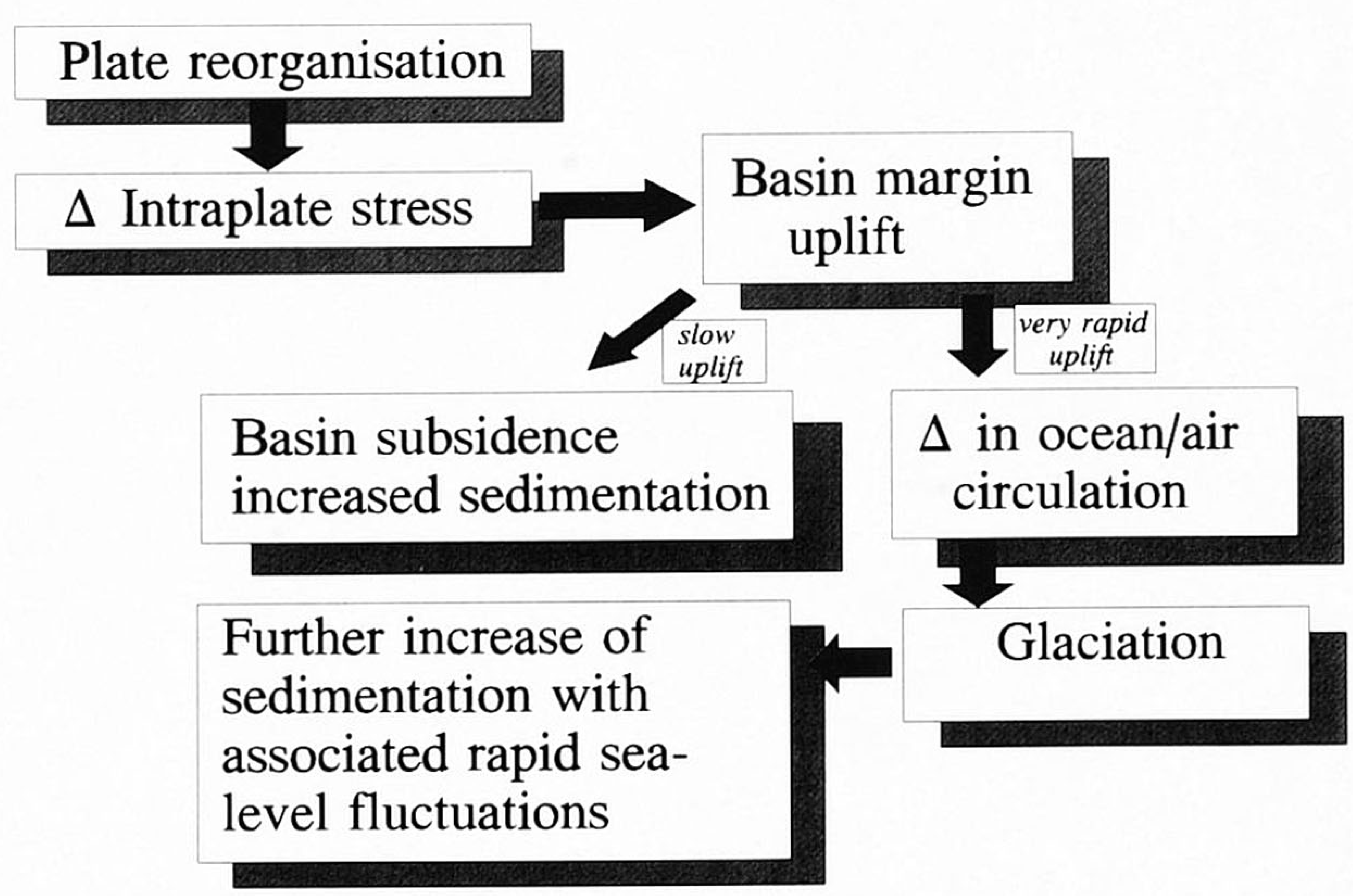

Fig. 8. *Stress-induced uplift: effect on (de)glaciation. Schematic diagram illustrating proposed relations between tectonics, basin subsidence and the record of sea-level changes (After Cloetingh* et al.*, 1990).*

eastern North Sea and Palaeogene to Palaeozoic strata subcrop towards the Fennoscandian shield. The uplift, which was caused by broad-scale regional warping without any major faulting, has important consequences for hydrocarbon exploration in the affected areas (Jensen and Schmidt, 1992). Changes in basement topography induced by compression are also important in changing the dynamics of fluid flow in rifted basins (Van Balen and Cloetingh, 1992), promoting the development of overpressures in rifted basins and affecting estimates for stretching factors (Kooi and Cloetingh, 1989a).

The 'atectonic' regional warping and monoclinal development seems to be the norm (Dore, 1992). Active faulting takes up part of the movement, however, in east Greenland (Larsen, 1984) and along the Barents Sea margin (Lippard and Fanavoll, 1992). Seismic reflection data along the Norwegian continental margin show that major compressional structures were active until Early Pliocene followed by a cessation of small-wavelength compressional deformation (R. Muir Wood, pers. comm., 1992), possibly in conjunction with a partial relaxation of compressional stresses. The subsequent long-wavelength deformation, invoking large-scale warping (Dore, 1992), is sometimes misunderstood as passive subsidence. Similarly, in the southern North Sea Sole Pit Basin significant small-scale compressional deformation was in operation until the early Miocene but the subsequent sediments are not affected by short-wavelength deformation (R. Muir Wood, pers. comm., 1992). An interesting analogy exists here with the large-scale folding initiated in the uppermost Miocene in the northeastern Indian Ocean (Stein *et al.*, 1990) which probably also followed a phase of short-wavelength shortening and reverse faulting. The wavelength of the observed deflection across the Norwegian margin (Dore, 1992) is consistent with flexure induced by sediment loading (Cloetingh *et al.*, 1982; Watts *et al.*, 1982), while the observed amplitude of the vertical deflection points to an amplification by intraplate compression. The present day stress field off the Norwegian margin has been investigated using break-out techniques (Spann *et al.*, 1991) and is characterized by an orientation roughly perpendicular to the margin.

The Northern Atlantic and the Arctic have been the site of a relatively high level of tectonic activity in Late Cenozoic times, while recent (Karpuz *et al.*, 1991) studies of neotectonics and seismicity (see also Stein *et al.*, 1989 for a review) also demonstrates a high level of intraplate deformation for the Norwegian 'passive' continental margin. Unloading of Fennoscandia and the associated glacial erosion provide an important contribution to the vertical motions in the Barents Sea and Norwegian margin. However, the characteristic magnitude of the glacial erosion associated with the removal of the ice sheet – of the order of a few hundred metres (Stein *et al.*, 1989) – requires the involvement of another mechanism to generate the observed thickness of offshore Plio-Quaternary sedimentary wedges and to explain the magnitude of the inferred inner margin erosion (Cloetingh *et al.*, 1990). Riss and Fjeldskaar (1992), in calculating the isostatic response of erosion from the Barents Sea and Fennoscandia and the corresponding deposition of the shelves, came to the same conclusion. Using maximum models for the amount of glacial erosion they inferred a strong component of tectonic uplift in Fennoscandia which cannot be explained by a passive response to glacial processes. According to these authors, the subsidence of the shelves appears to be greater than could be predicted by the passive unloading models, with a missing tectonic component larger in the onshore mountain areas of Norway and smaller in the Barents Sea.

Thus it seems that uplift-induced glaciation by Himalayan and Rocky Mountain plateaux uplift could be augmented by uplift-induced glaciation along the northern Atlantic itself. The simultaneous occurrence of glacial unloading and tectonically enhanced uplift of Fennoscandia would imply that current estimates of ice thickness based on the study of the postglacial rebound uplift history, ignoring a tectonic component to the uplift, are too high.

Rapid vertical motions at the flanks of rifted basins at a time long after their formation have also been documented outside the Northern Atlantic/Mediterranean region. For example, rapid uplift has occurred in late Cenozoic times along the onshore part of rifted continental margins in the southern Atlantic leading to pronounced topography at the Brazilian margin (Chang *et al.*, 1990) and segments of the African margin. Coeval to the distortions of the patterns of decreasing thermal subsidence, changes in the geometry and spreading rates of the Equatorial and South Atlantic Ridge have been documented during the last 10 Myr by Brozena (1986). Far outside the Atlantic, late Cenozoic unconformity generation and abrupt changes in subsidence have also been documented for the Northwestern Australian margin (Cloetingh *et al.*, 1992b) and reflect the timing of the onset of intraplate deformation in the northeastern Indian Ocean (Stein *et al.*, 1990).

In a number of regions in Antarctica and in the Arctic, flank uplift due to necking of the lithosphere during basin formation has played an important role in the creation of topography. Necking of the lithosphere during Mid-Tertiary rifting of the Norwegian Greenland Sea has formed the present topography with steep rift shoulders in the Svalbard archipelago in the Arctic. This process has also controlled the formation of the Transantarctic mountains (Fitzgerald *et al.*, 1987) in Tertiary times. Seismic profiling of the sedimentary sequences at the Ross Sea embayment (Bartek *et al.*, 1991) has provided evidence for phases of tilting and the associated truncation of Palaeogene and Neogene strata at the inner parts of the continental margin during late Neogene times. Considering the importance of the Antarctic ice cap (e.g. Van der Veen and Oerlemans, 1987), and the crucial role of topography in controlling the stability of ice caps (Van der Veen, 1987), the interplay of tectonics and (de)glaciation warrants more quantitative study.

DISCUSSION AND CONCLUSIONS

From the foregoing, it appears that ample evidence exists for rapid phases of anomalous subsidence in late Cenozoic times, possibly in connection with changes in intraplate stress regimes at that time. It seems, therefore, that at the sites of 'passive' margins and intraplate settings not subject to active tectonics, subtle but rapid vertical motions are induced by far-field tectonics. The observed accelerations in subsidence in the northern Atlantic/North Sea region go in concert with stress-induced uplifts of continental regions located at the flanks of the rift basins. The interplay of stress-induced topography with the dynamics of (de)glaciation could be of significant importance for understanding the processes underlying much of the Plio-Quaternary record.

As pointed out by Dore (1992), the highly episodic nature of Tertiary sedimentation adjacent to the Fennoscandian landmass with a strong Pliocene rejuvenation indicate an active and temporally variable tectonic drive for the deformation. A noteworthy feature is the shape of the deformation being characterized by gentle warping without significant reactivation of Mesozoic faults. It appears that tectonically-generated uplift in the late Cenozoic, in combination with the known global climate cooling trend of the Cenozoic, may have itself triggered the glaciation. Of particular importance in this respect seems to have been the joint effects of spreading reorganizations in the Northern Atlantic and closure events in the Alpine/Mediterranean region.

Apart from stress-induced uplift, other tectonic processes that operate in rift basin formation have contributed to the formation of topography underlying present-day ice caps. Lithospheric necking during Tertiary rifting in the Antarctic and Arctic regions is of particular importance in this respect. In view of the role that topography plays in the dynamics of ice sheets, future quantitative studies of Antarctic and Arctic basins are of particular interest. Such studies are also relevant for estimates of ice cap volumes inferred from uplifts of glacial terranes. The late Cenozoic record contains a tectonic signal strong enough to be recognized amidst climate driven contributions. The simultaneous occurrence of what appears to be a high level of neotectonic activity and the dynamics of (de)glaciation suggests that the interplay of tectonics and climate has been particularly intensive during this time slice. It seems, therefore, questionable whether the Plio-Quaternary record provides a simple end member for comparison with the geological record in Tertiary and Mesozoic times.

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