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Thermo-mechanical modelling of Black Sea Basin (de)formation

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Abstract

We present the results of a thermo-mechanical modelling study carried out to investigate the effect of pre-rift rheology on subsequent basin (de)formation in the Black Sea area. Important differences are inferred for the bulk lithosphere structure and mechanical properties, expressed in terms of different estimates for levels of necking in the western and eastern Black Sea, respectively. Gravity data provide constraints on the mode of flexure in the Black Sea, pointing to significant lateral variations in pre-rift lithospheric strength. These features strongly affect predictions for Mesozoic–Cenozoic Basin stratigraphy and have implications for the presence and development of rift shoulder topography on the margins of the Black Sea Basins. Differences in lithosphere strength affect the mode of stress propagation from the basin margins into the central parts of the Black Sea Basins during the post-rift phase. These post-rift compressional stresses could be of key importance for long-wavelength Late Neogene differential motions within the basins, superimposed on vertical motions induced by rifting and subsequent sediment loading. Thermo-mechanical modelling of integrated lithospheric strength points to a rapid increase of strength during the later stages of post-rift evolution and the presence of relatively strong lithosphere in the centre of the basin. These features predict preferential shortening induced by compressional activity of surrounding orogens to be primarily accommodated at the basins' margins.

Keywords: Thermo-mechanical modelling; Lithosphere memory; Black Sea; Intraplate stress; Neotectonics

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1. Introduction

The Mesozoic–Cenozoic evolution of the Black Sea, reviewed in a number of key papers (Zonenshain and Le Pichon, 1986; Dercourt et al., 1986; Finetti et al., 1988; Okay et al., 1994; Jones and Simmons, 1997; Robinson et al., 1995; Robinson, 1997; Banks and Robinson, 1997; Spadini et al., 1997; Nikishin et al., 1998, 2001) has been generally interpreted in terms of Late Cretaceous–Eocene back-arc extension. The exact timing and kinematics of opening of the west and east Black Sea Basins is the subject of ongoing debates (e.g. Nikishin et al., 2001; Robinson et al., 1995). This applies in particular to the exact timing of the opening of the eastern Black Sea where different interpretations have been put forward varying from Middle to Late Cretaceous opening (Finetti et al., 1988) to Paleocene opening (Robinson et al., 1995).

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In this study, we present the results of thermo-mechanical modelling of the Black Sea Basin carried out for a number of cross-sections through the western Black Sea and eastern Black Sea, respectively (Fig. 1). The modelling is constrained by a large integrated geological and geophysical data base (see Spadini, 1996; Spadini et al., 1996, 1997), supporting the interpretation of Robinson et al. (1995) for a Paleocene opening of the eastern Black Sea. This timing for the eastern Black Sea is partly based on the presence of a regional unconformity separating Maastrichtian and Eocene deposits in the eastern Black Sea and which is interpreted as the result of rift shoulder uplift. It should be noted that the same unconformity is interpreted by Nikishin et al. (2003) in terms of Late Cretaceous compressional tectonics along the southern margin of Eastern Europe. On this basis, these authors favour a simultaneous Cenomanian–Coniacian opening of the western and eastern Black Sea. Gravity data demonstrate an important difference in the mode of flexural compensation between the western and eastern Black Sea (Spadini et al., 1997). The western Black Sea appears to be isostatically undercompensated and in a state of upward flexure, consistent with a deep level of necking. In contrast, the eastern Black Sea gravity data and their comparison with models point to an isostatic overcompensation and downward state of flexure, compatible with a shallow level of necking (Fig. 2). These differences in necking depth reflect differences in pre-rift mechanical properties of the lithosphere underlying the western and eastern Black Sea Basins (see Spadini et al., 1996; Cloetingh et al., 1995b for reviews). Below, we discuss the importance of pre-rift finite strength for basin geometries in extending lithosphere. This is followed by a discussion of the effects of differences in pre-rift rheology on Mesozoic–Cenozoic Basin stratigraphy. These findings raise important questions

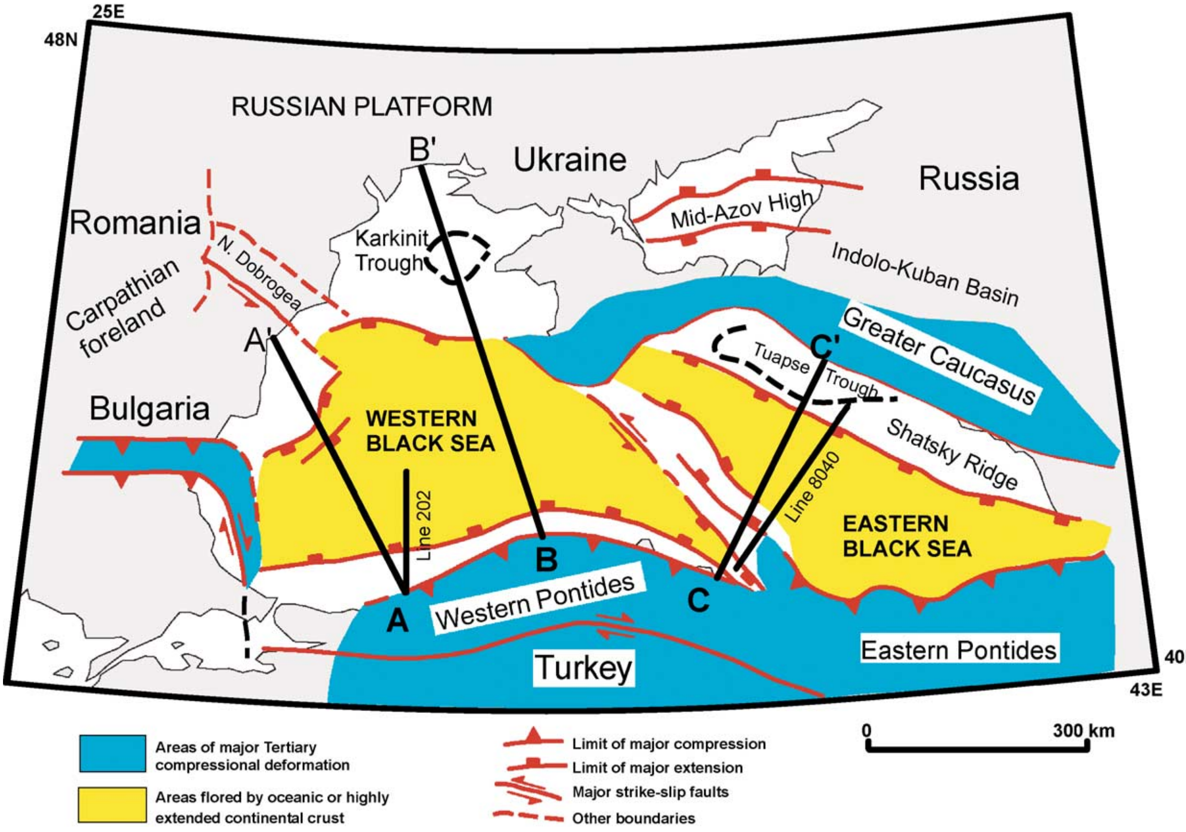


Fig. 1. Location map of modelled profiles in western and eastern Black Sea.

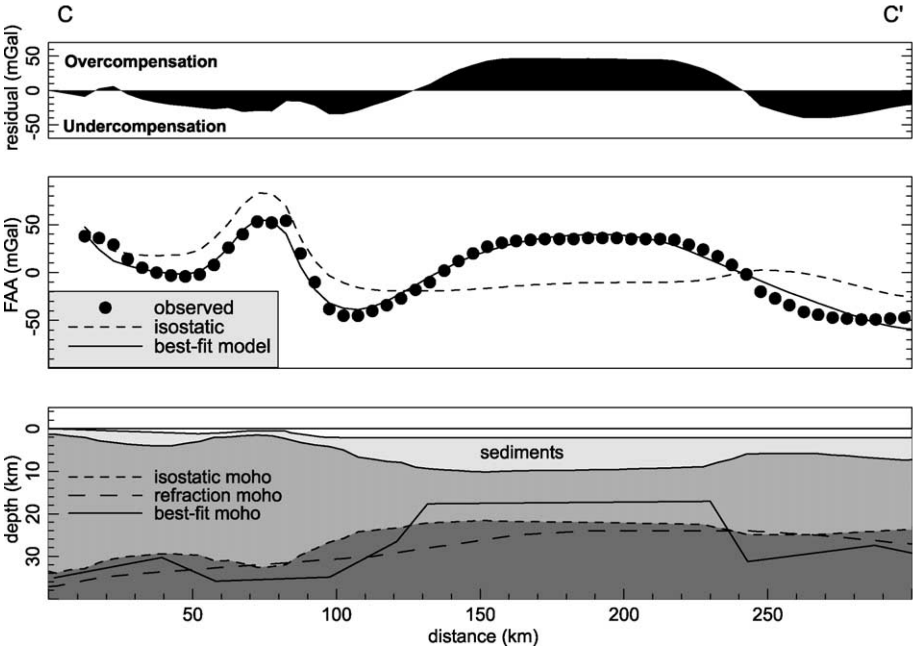


Fig. 2. Results of gravity modelling for eastern Black Sea, demonstrating an isostatic flexural overcompensation in the centre of the basin. See Fig. 1 for location of line C–C′.

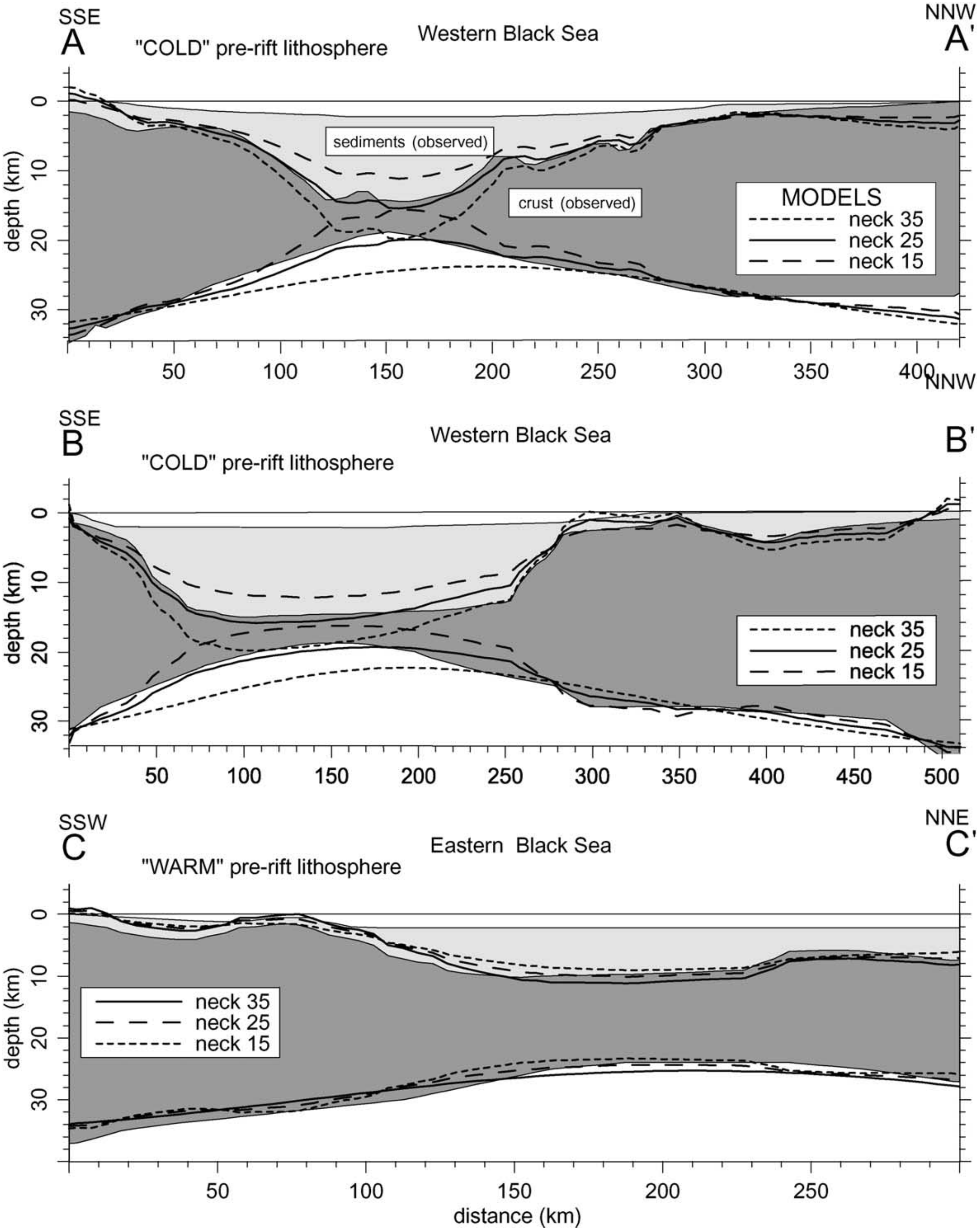
on post-rift tectonics, intraplate stress transmission into the Black Sea Basin from its margins and on the development of rift shoulders in the area.

2. Rheology and basin formation

Bulk rheological models of the lithosphere (Carter and Tsenn, 1987; Ranalli and Murphy, 1987; Kohlstedt et al., 1995), employing the concept of strength envelopes are based on extrapolation of rock mechanics data, combined with assumptions on petrological stratification and incorporating constraints from thermal modelling. These models have provided a useful, first-order framework for the analysis of the variations in mechanical structure of the lithosphere (Burov and Diament, 1995; Cloetingh and Burov, 1996). Spatial variations in strength distribution occur on a plate-wide scale, largely related to changes in crustal thickness and thermo–tectonic age (Cloetingh and Burov, 1996).

The importance of the role of pre-rift rheology in extensional basin formation has become evident from a systematic study of a large number of Alpine/Mediterranean Basins and intracratonic rifts (Cloetingh et al., 1995a,b). At the onset of rifting, the rheological structure of the lithosphere controls the location, structural style and width of the evolving rift systems, as well as the necking depth of the lithosphere (Cloetingh et al., 1995b). The incorporation of the mechanical strength of the lithosphere in extensional basin modelling is an important ingredient in these large-scale modelling studies (Braun, 1992; Beekman et al., 2000; Van Wees and Beekman, 2000; Huismans et al., 2001). The integration with the modelling of tilted fault blocks has also demonstrated its key importance for models targeting on subbasin-scale problems (Ter Voorde and Cloetingh, 1996).

Inferred differences in the mode of basin formation between the western and eastern Black Sea Basins can be expressed in terms of paleo-rheologies (see Fig. 3), pointing to a pre-rift strength in the western Black Sea primarily controlled by the combined mechanical response of a strong upper crust and strong upper mantle. The shallow level of necking in the eastern Black Sea is compatible with a pre-rift strength controlled by a strong upper crust decoupled from a weak, hot underlying mantle. These differences point to important differences in the thermo–tectonic age of


SSE
A
"COLD" pre-rift lithosphere
Western Black Sea
NNW
A'
sediments (observed)
crust (observed)
MODELS
neck 35
neck 25
neck 15
depth (km)
0
10
20
30
50
100
150
200
250
300
350
400
SSE
B
Western Black Sea
"COLD" pre-rift lithosphere
NNW
B'
neck 35
neck 25
neck 15
depth (km)
0
10
20
30
50
100
150
200
250
300
350
400
450
500
SSW
C
Eastern Black Sea
"WARM" pre-rift lithosphere
NNE
C'
neck 35
neck 25
neck 15
depth (km)
0
10
20
30
50
100
150
200
250
distance (km)

the lithosphere in the two subbasins (Cloetingh and Burov, 1996). The inferred lateral variations between the western and eastern Black Sea suggests thermal stabilization of the western Black Sea prior to rifting. In contrast, the eastern Black Sea was already a basin by the time of rift initiation, with a previously thinned crust.

3. Large-scale basin stratigraphy

The inferred lateral variations in pre-rift mechanical properties have important consequences for basin stratigraphy. This does not only affect the development of syn-rift shoulders (see the discussion in Cloetingh et al., 1995b), but also the interplay of rift shoulder development and subsequent erosion during the post-rift stage (Van Balen et al., 1995; Burov and Cloetingh, 1997). These processes could lead to strong deviations in thinning factors for lithosphere extension and tectonic subsidence patterns inferred from predictions of classical stretching models (McKenzie, 1978), ignoring the presence of pre-rift strength in extending lithosphere. At the same time, they have been shown to be able to generate post-rift unconformities, primarily controlled by rift shoulder erosion dynamics. A key aspect in this dynamic link between rift shoulder uplift and basin subsidence appears to be the amount of mechanical decoupling between the upper crust and upper mantle segments of the extending lithosphere (Ter Voorde et al., 1998).

Figs. 4 and 5 show observed and modelled stratigraphies along the two selected profiles in the western and eastern Black Sea, respectively. Fig. 6 illustrates the evolution of basin subsidence and water-loaded tectonic subsidence (Steckler and Watts, 1978; Bond and Kominz, 1984) in time, calculated for both the Odin (1994) and Harland et al. (1990) time scales. Subsidence curves are displayed for locations at the centre and the basin margin of western and eastern Black Sea, respectively. The western Black Sea began rifting in the Late Barremian and by the Cenomanian was a deep marine basin with oceanic crust and limited syn-rift sediments towards the basin centre. The deep basin persisted until the Sarmatian sea level fall, which reduced the basin to a relatively small lake up to around 800 m in the centre. The eastern Black Sea began rifting in the Late Paleogene and subsided rapidly with little rift flank uplift or erosion to form a deep marine basin. During the Late Eocene, an increase in sediment supply from compressional belts to the Pontides or possibly Greater Caucacus led to the deposition of a thick upper Eocene sequence. The eastern Black Sea remained a deep basin until the Sarmatian, and subsequently was converted into a lake during the Sarmatian. As sea level returned to normal in the Late Miocene, water depth increased dramatically to 2800 m in both western and eastern Black Sea Basins due to the loading effect of the water. By the Quaternary, increased sediment supply led to significant subsidence and sediment accumulation, with a modest decrease of water depth to the present-day value of 2200 m.

Overall uplift of the margins of the Black Sea commenced at Middle Miocene times (Nikishin et al., 2003). Differences occur between the reconstructions of Nikishin et al. (2003) and Spadini et al. (1997) on the maximum basin depth and paleobathymetry and sea level change during basin formation time. Notwithstanding these differences, the Pliocene–Quaternary acceleration in subsidence (Spadini et al., 1997; Robinson et al., 1995) appears to be a robust fracture reconfirmed by Nikishin et al. (2003).

4. Rift shoulder dynamics, intraplate stresses and strength evolution during the post-rift phase

4.1. Rift shoulder dynamics

The post-rift evolution of extensional basin is governed by cooling and contraction of the lithosphere and its re-equilibration with the asthenosphere (McKenzie, 1978).

Important questions to be resolved concern the rift shoulder erosion and its effect on sediment supply to the basin as well as the role of stresses during the

Fig. 3. Crustal scale models for extensional basin formation for the western and eastern Black Sea. See Fig. 1 for location of cross sections. A comparison of predicted and observed Moho depths provides constraints on levels of necking and thermal regime of pre-rift lithosphere. The models support the presence of cold pre-rift lithosphere compatible with a deep level of necking of 25 km in the western Black Sea. In the eastern Black Sea, the models suggest the presence of a warm pre-rift lithosphere with a level of necking of 15 km.

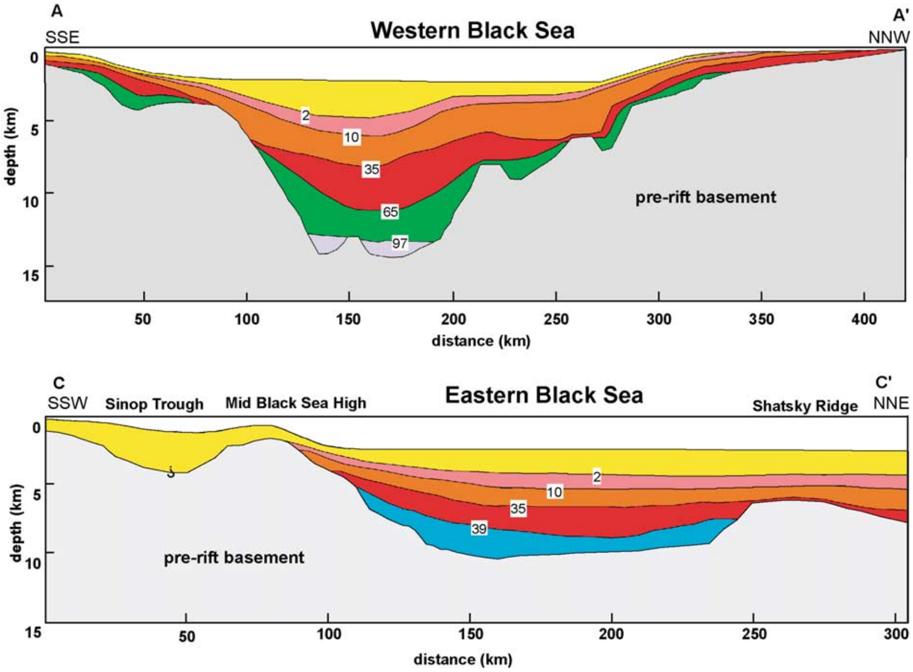


Fig. 4. Observed first-order geometries for basement configuration and sediment infill, characteristic for western and eastern Black Sea. Numbers refer to stratigraphic ages (Ma). Note the substantial thickness of Quaternary sediment infill. See text for further discussion. See Fig. 1 for location of sections A–A′ and C–C′.

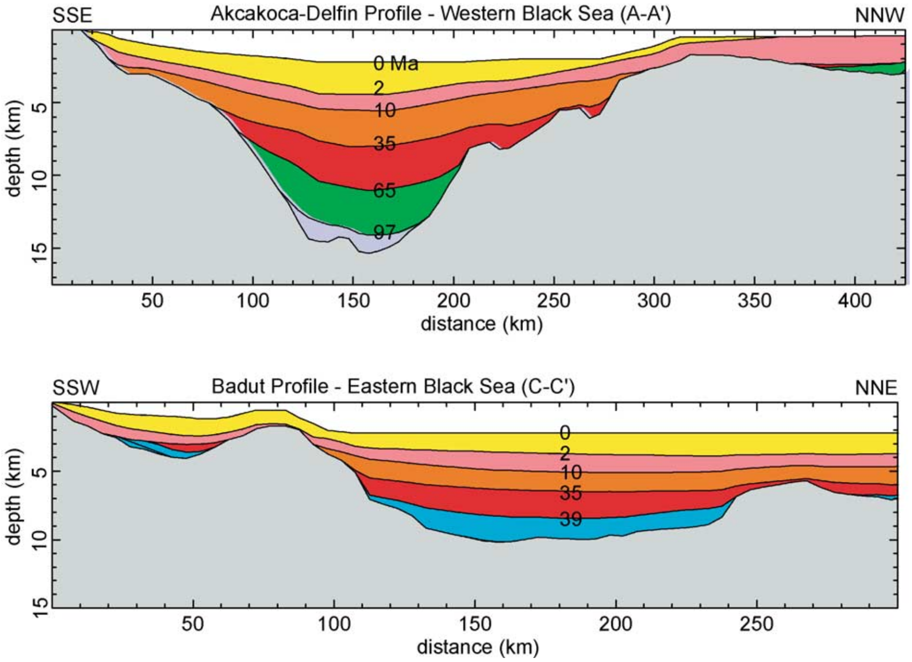


Fig. 5. Modelled stratigraphies and basement topography for profiles shown in Fig. 4 in western and eastern Black Sea. Adopted levels of necking, constrained by gravity modelling, are 25 and 15 km for western and eastern Black Sea, respectively.

post-rift phase. In the last few years (see e.g. Cloetingh et al., 1993, 1995a, 1997; Gabrielsen and Strandenes, 1994), basin modelling is shifting its scope from an initial focus on subsidence and geometry of accommodation space into the modelling of the feedback of the processes of sedimentation and erosion (e.g. Burov and Cloetingh, 1997; Cloetingh et al., 1997). This development creates the need for better constraints on the evolution of topography in space and time. In modelling extensional basins, the reconstruction of rift shoulder topography (Van der Beek et al., 1994) through fission track data (Rohrmann et al., 1995) and exposure dating is becoming increasingly common. The results of these studies are becoming capable of quantifying the simultaneous occurrence of various climatic and tectonic processes during the evolution of the flanks of rifted margins. The modelling of near-surface processes is also suggesting a close feedback with deep crustal flow (Burov and Cloetingh, 1997), affecting concepts on the tectonic control on sequence boundaries related to uplift history (Van Balen et al., 1995).

The inferred differences in necking level and in the timing of rifting between the western and eastern Black Sea suggests an earlier and more pronounced development of rift shoulders in the western Black Sea Basin in comparison with the eastern Black Sea.

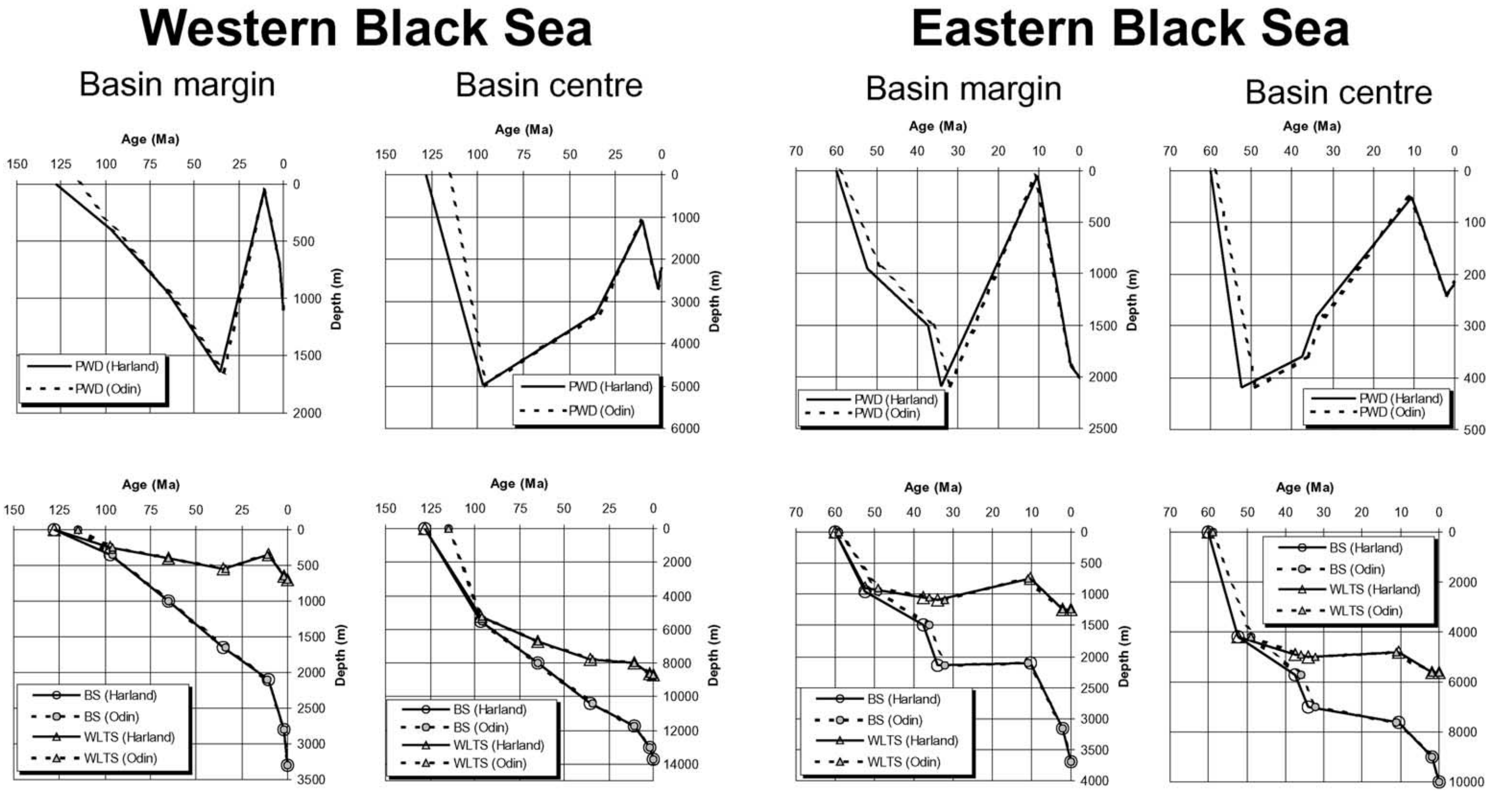
4.2. Intraplate stresses

It is now recognized that intraplate domains are characterized by a far more dynamic history than hitherto assumed, affecting tectonic geomorphology and recognizable in shallow seismics in areas such as the Pannonian Basin and the North Sea Basin (Horvath and Cloetingh, 1996; Van Wees and Cloetingh, 1996). Constraints on present-day stress regime are absent for the central part of Black Sea Basin. Structural geological field studies (see review by Nikishin et al., 2001) and GPS data (Reilinger et al., 1997) demonstrate that in the collisional setting of the European and Arabian plate compression continues. Closer monitoring and modelling of fluxes in conjunction with more focus on the neotectonics of Black Sea Basins is obviously a must. Field studies of kinematic indicators and numerical modelling of present-day and paleo-stress fields in selected areas (e.g. Gölke and Coblentz, 1996; Bada et al., 1998, 2001) have yielded new constraints on the causes and expressions of intraplate stress fields in the lithosphere. Ziegler et al. (1998) have discussed the key role of mechanical controls on collision related compressional intraplate deformation. These authors discuss the build-up of intraplate stresses in relation to the mechanical coupling of an orogenic wedge to its fore- and hinterland as well as the implications to the understanding of a number of first-order features in crustal and lithospheric deformation.

Temporal and spatial variations in the level and magnitude of these stresses have a strong impact on the record of vertical motions in sedimentary basins (Cloetingh et al., 1985, 1990; Cloetingh and Kooi, 1992; Zoback et al., 1993; Van Balen et al., 1998). Propagation of stresses from the basin margins into the interior part of the Black Sea Basin could not only have a strong effect on the stratigraphic record, but also for stresses with a level close to lithospheric strength generate a component of folding-induced, late-stage subsidence (Cloetingh et al., 1999), similar to what has been recognized for the Pannonian Basin and the North Sea Basin (Horvath and Cloetingh, 1996; Van Wees and Cloetingh, 1996). Over the last few years, increasing attention has been directed into this topic, advancing our understanding into the relationships between plate motion changes, plate interaction and the evolution of rifted basins (Janssen et al., 1995; Dore et al., 1997) and foreland areas Ziegler et al. (1995, 1998, 2001).

A continuous spectrum of stress-induced vertical motions can be expected in the sedimentary record, varying from the subtle effects of faulting (Ter Voorde and Cloetingh, 1996; Ter Voorde et al., 1997) and basin inversion (Brun and Nalpas, 1996; Ziegler et al., 1998) to enhancement of flexural effects to lithosphere folds induced for high levels of stress approaching lithospheric strengths (Stephenson and Cloetingh, 1991; Nikishin et al., 1993; Burov et al., 1993; Cloetingh and Burov, 1996; Bonnet et al., 1998; Cloetingh et al., 1999).

Crustal and lithospheric folding can be an important mode of basin formation in plates involved in continental collision (Cobbold et al., 1993; Ziegler et al., 1995, 1998; Cloetingh et al., 1999). Numerical



Western Black Sea

Basin margin

Basin centre

Eastern Black Sea

Basin margin

Basin centre

Fig. 6. Results of backstripping analysis for positions at margins and centre of western and eastern Black Sea, respectively. Top panels show palaeo water depth (PWD), bottom panels show basement subsidence (BS) and water-loaded tectonic subsidence (WLTS). Each curve is calculated for two different time scales (Odin, 1994; Harland et al., 1990) to illustrate sensitivity.

models have been developed for the simulation of the interplay of faulting and folding in intraplate compressional deformation (Beekman et al., 1996; Gerbault et al., 1998; Cloetingh et al., 1999). Models have also been developed to investigate the effects of faulting on stress-induced intraplate deformation in rifted margin settings (Van Balen et al., 1998).

The collisional Caucasus orogeny commenced at the end of the Eocene with a culmination during Oligocene–Quaternary times (Nikishin et al., 2001). The late Eocene accelerated subsidence of the Black Sea Basin can be attributed to the build-up of a regional compressional stress field (Robinson et al., 1995).

The late Eocene–Quaternary Caucasus orogeny overprinting back-arc extension in the Black Sea was controlled by the collisional interaction with the East European craton (Nikishin et al., 2001).

4.3. Lithospheric strength of the Black Sea Basin

Automated backstripping and comparison with forward models of stretching (Van Wees et al., 1998) allow to obtain estimates for the integrated strength of the lithosphere for various stages of the syn-rift and post-rift phase. The adopted model parameters are listed in Tables 1 and 2.

Fig. 7 shows a comparison of observed and forward-modelled tectonic subsidence for the western Black Sea centre. Automated backstripping yields an estimate for stretching factor beta of 6. The modelling fails to predict a pronounced acceleration of late Neogene subsidence, documented in the stratigraphic record, which could be an indication of late-stage compression. The post-rift cooling leads to a significant increase in the predicted integrated strength with time. Based on this, post-rift deformation will be favoured during early post-rift time. Present-day lithospheric strength profiles calculated for the centre and margin of eastern Black Sea show a pronounced difference. The presence of relatively strong lithosphere in the basin centre will enhance late-stage compressional shortening induced by orogenic activity in the areas adjacent to the Black Sea to be initially accommodated preferentially at the basin margins.

Fig. 8 displays the comparison between observed tectonic subsidence and forward-modelled tectonic subsidence for the centre of the eastern Black Sea, adopting a stretching factor of 2.3 compatible with the subsidence data, and consistent with geophysical constraints. During the first 10 million years of post-rift evolution, integrated strengths are low, followed by a rapid increase induced by post-rift cooling. Based on the presence of very weak lithosphere in the eastern Black Sea in the first 10 million years after rifting, we expect that such an early post-rift deformation controlled primarily by the mechanical properties of the upper lithosphere inherited from the rifting phase could be preferentially developed in that area. It should be noted that the rapid increase of the integrated lithospheric strength with post-rift cooling requires increasingly higher stress levels with time to induce noticeable large-scale deformation (see Fig. 8). What is also important in this context is that due to the substantial amount of crustal thinning, a strong

Table 1
Model parameters used to calculate the tectonic subsidence in the rheological models

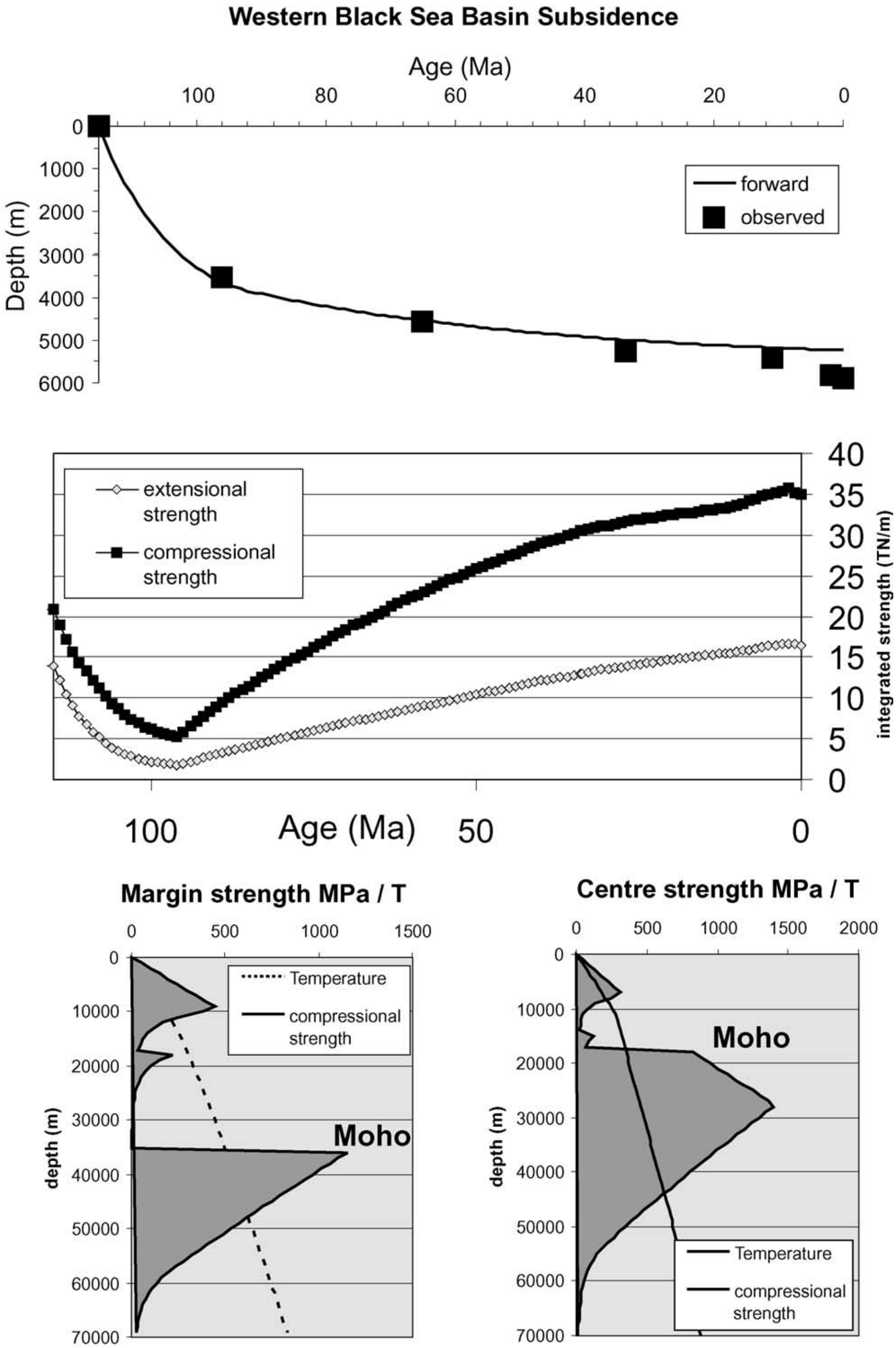
Symbol	Model parameter	Value
A	initial lithosphere thickness	120 km (WB), 80 km (EB)
C	initial crustal thickness	35 km
T_m	asthenospheric temperature	1333 °C
K	thermal diffusivity	1×10^{-6} m^2 s^{-1}
ρ_c	surface crustal density	2800 kg m^{-3}
ρ_m	surface mantle density	3400 kg m^{-3}
ρ_w	water density	1030 kg m^{-3}
α	thermal expansion coefficient	3.2×10^{-5} K^{-1}
β	crustal stretching factor	6 (WB), 2.3 (EB)
δ	subcrustal stretching factor	6 (WB), 2.3 (EB)

The (EB) and (WB) refer to eastern and western Black Sea, respectively.

Table 2
Default rheological and thermal properties of crust and lithosphere

Layer	Rheology	Conductivity (W m^{-1} K^{-1})	Heat production (μW m^{-3})
Sediments	quartzite (d)	1.5	0.5
Upper crust	quartzite (d)	2.9	2
Lower crust	diorite (w)	2.9	0.5
Upper mantle	olivine (d)	2.9	0

The (d) and (w) refer respectively to dry or wet rock samples that contain little or variable amounts of structural water. For more details on the rheological rock properties see Van Wees and Beekman (2000).


Western Black Sea Basin Subsidence
Age (Ma)
100
80
60
40
20
0
Depth (m)
0
1000
2000
3000
4000
5000
6000
forward
observed
extensional strength
compressional strength
integrated strength (TN/m)
40
35
30
25
20
15
10
5
0
100
Age (Ma)
50
0
Margin strength MPa / T
0
500
1000
1500
depth (m)
0
10000
20000
30000
40000
50000
60000
70000
Temperature
compressional strength
Moho
Centre strength MPa / T
0
500
1000
1500
2000
depth (m)
0
10000
20000
30000
40000
50000
60000
70000
Moho
Temperature
compressional strength

upper mantle layer is present in the central part of the basin at relatively shallow depths.

4.4. Neotectonic reactivation of the Black Sea Basin

Based on the present thermo-mechanical configuration (see Fig. 8) with relatively strong lithosphere in the basin centre and relatively weak lithosphere at the basin margins, we predict that a substantial amount of late-stage shortening induced by orogenic activity in the surrounding areas will be taken up by the basin margins, with only minor deformation in the relatively stiff centre part of the basin. The relative difference in rheological strength in the eastern Black Sea is much more pronounced than in the western Black Sea. These predictions have to be validated by new data focusing on neotectonics of the Black Sea. High-resolution shallow seismics and acquisition of stress-indicator data could provide the necessary constraints for such future modelling.

Fig. 9 gives predictions for basement and surface heat flow in the eastern and western Black Sea and shows markedly different patterns in timing of heat flow maximum, close to the timing of initial rifting. The predictions for present-day heat flow in the western Black Sea are considerably lower than in the eastern Black Sea, as a consequence of the stronger attenuation of the crust which has resulted in removal of more heat producing material in the crust in the western Black Sea compared to the eastern Black Sea. In the modelling of heat flow, the effects of sedimentary blanketing have been taken into account (Van Wees and Beekman, 2000). Present-day heat flow in the Black Sea Basin is strongly affected by the blanketing effect from such sedimentary successions. Heat flow values vary between 30 mW/m^2 in the centre of the basins and 70 mW/m^2 in the Crimea and Caucasus margins of the basin (Nikishin et al., 2003). Note the pronounced effect of thermal blanketing in the western Black Sea in conjunction with major sediment infill. As a result, the present-day integrated strength is not that much higher as the initial strength. In contrast, the integrated strength of the eastern Black Sea is much higher than the initial strength. The blanketing effect is less pronounced due to less sediment deposition and larger water depths.

Fig. 10 shows a comparison of theoretical predictions for lithosphere folding in rheologically coupled and decoupled lithosphere, as a function of thermo-mechanical age with estimates of folding wavelengths documented in continental lithosphere for various representative areas on the globe (see Cloetingh et al., 1999). The western Black Sea centre is marked by a thermo-mechanical age of 100 Ma. The rheological modelling demonstrates mechanical decoupling of mantle and crustal lithosphere (see Fig. 7). These models imply an effective elastic thickness (EET) of at least 40 km (Burov and Diament, 1995), which results in folding with wavelengths of around 100–200 km for mantle and 50–100 km for upper crust (Cloetingh et al., 1999). In the eastern Black Sea, with a significantly younger thermo-mechanical age of 55 Ma, implying an EET of no more than 25 km indicates a mantle-folding wavelength of ca. 100–150 km. The crustal folding wavelength is similar as in the western Black Sea. A comparison of the estimates of folding wavelengths with the theoretical predictions shows a systematic deviation of the wavelengths to larger values. This is characteristic for "atypical" folding where the geometry of the preexisting rift basin with its large dimension has a pronounced effect on widening the wavelength of the compressional stress-induced down warp during the late-stage post-rift phase (Cloetingh et al., 1999). A similar behaviour has been recognized for the North Sea Basin (Van Wees and Cloetingh, 1996) and the Pannonian Basin (Horvath and Cloetingh, 1996), both basins characterized by large sediment loads and a wide rift basin

Fig. 7. A comparison of observed and forward-modelled tectonic subsidence for the western Black Sea centre. Automated backstripping yields an estimate for stretching factor beta of 6 (top panel). A pronounced acceleration of late Neogene subsidence (see also Fig. 6) documented in the stratigraphic record could be an indication of late-stage compression. Post-rift cooling leads to a significant increase in the predicted integrated strength with time for both compressional and extensional regimes (middle panel; 1 TN/m = 10^{12} N/m). Present-day lithospheric compressional strength profiles calculated for the centre and margin of western Black Sea show a pronounced difference with depth (bottom panels). Temperature profiles (in °C) and Moho depth are given for reference. Note the important role of the actual position Moho in mechanical decoupling of upper crust and mantle parts of the Black Sea lithosphere. The parameters used for the modelling of the tectonic subsidence and for the rheological strength are listed in Tables 1 and 2, respectively.

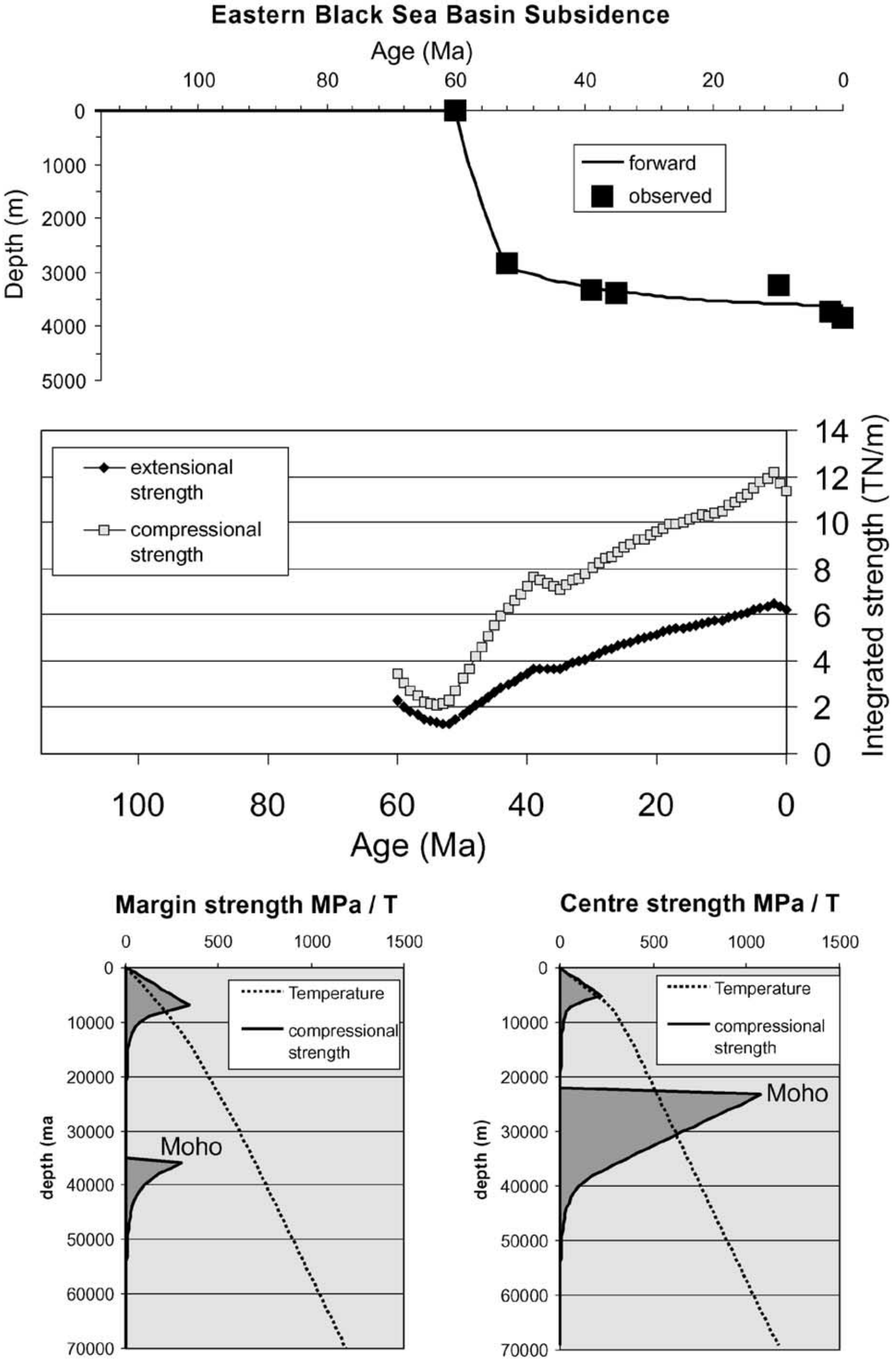


Fig. 8. Comparison of observed and forward-modelled tectonic subsidence for the eastern Black Sea centre. Automated backstripping yields an estimate for stretching factor beta of 2.3 (upper panel). Post-rift cooling leads to a significant increase in the predicted integrated strength with time for both compressional and extensional regimes (middle panel; 1 TN/m = 10^{12} N/m). Present-day lithospheric strength profiles calculated for the centre and margin of eastern Black Sea show a pronounced difference with depth (bottom panels).

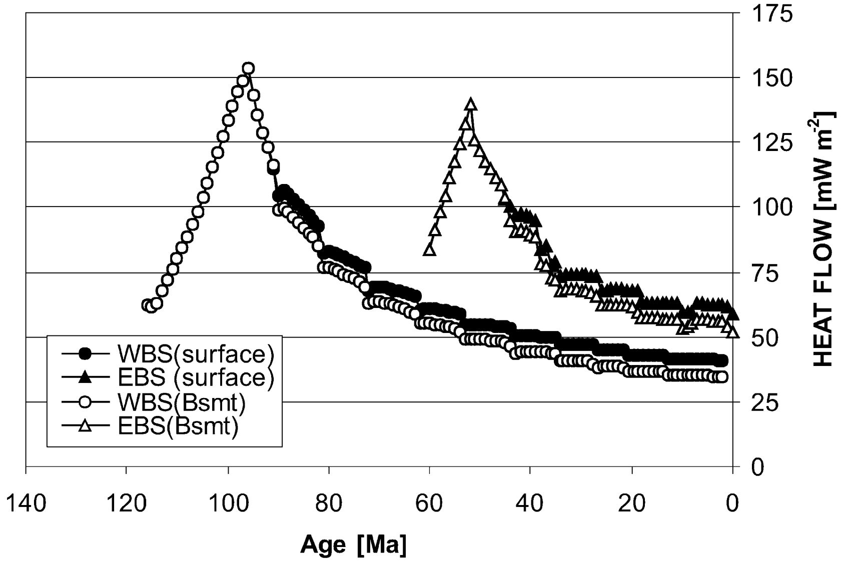


Fig. 9. Predictions for basement (Bsmt) and surface heat flow in the eastern (triangles) and western (squares) Black Sea show markedly different patterns in timing of heat flow maximum, close to the timing of initial rifting. The predictions for present-day heat flow in the western Black Sea are considerably lower than in the eastern Black Sea. See text for implications for difference in strength evolution between the western and eastern Black Sea.

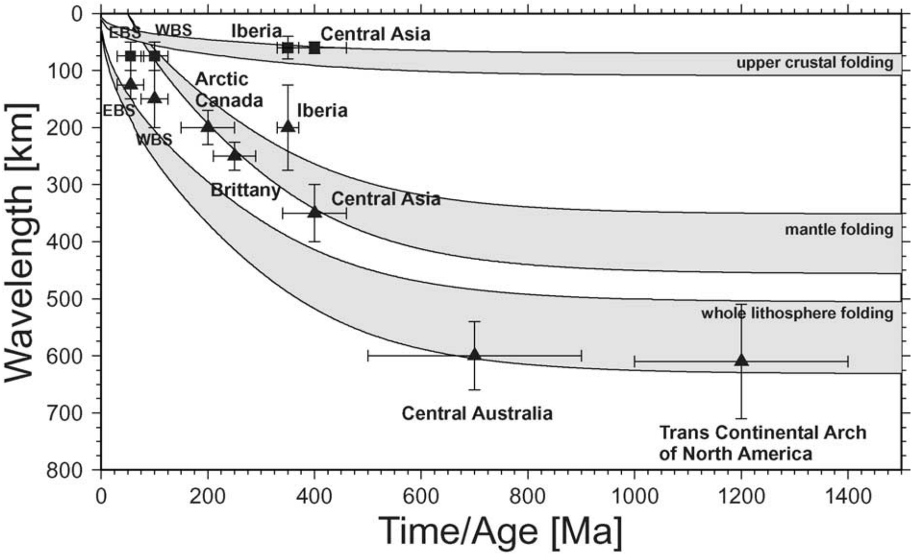


Fig. 10. Comparison of theoretical predictions for lithosphere folding in rheologically coupled and decoupled lithosphere, as a function of thermo-mechanical age with estimates of folding wavelengths documented in continental lithosphere for various representative areas on the globe (see Cloetingh et al., 1999). Comparison of the estimates of crustal and mantle folding wavelengths for the western Black Sea (WBS) and eastern Black Sea (EBS) with the theoretical predictions shows a systematic deviation of the wavelengths to larger values, characteristic for "atypical" folding. See text for further discussion.

geometry. The proposed mechanism for neotectonic reactivation provides an alternative to previous explanation for recent differential motions in the northern Black Sea Basin (Smolyaninova et al., 1996) interpreting the observed neotectonic activity in terms of convective mantle flow under the Black Sea. In view of the recent evidence for crustal shortening in the Black Sea region as a consequence of the Arabian plate/Eurasia interaction (Reilinger et al., 1997), an interpretation in terms of an enhanced Late Neogene level of compressional stress appears to be more likely.

According to our modelling, the eastern Black Sea Basin is much weaker than the western Black Sea. The eastern Black Sea is relatively stronger in the centre than at the margins, compared to the western Black Sea. The eastern Black Sea appears to be more prone to lithospheric folding, whereas the western Black Sea is more prone to stress transfer.

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References

Bada, G., Cloetingh, S., Gerner, P., Horvath, F., 1998. Sources of recent tectonic stress in the Pannonian region derived from finite element modelling. Geophys. J. Int. 134, 87–101.

Bada, G., Horvath, F., Cloetingh, S., Coblentz, D.D., 2001. Role of topography-induced gravitational stresses in basin inversion: the case study of the Pannonian Basin. Tectonics 20, 343–363.

Banks, C.J., Robinson, A.G., 1997. Mesozoic strike-slip back-arc basins of the western Black Sea. In: Robinson, A.G. (Ed.), Regional and petroleum geology of the Black Sea and surrounding areas. Am. Assoc. Pet. Geol., Mem. 68, pp. 53–62.

Beekman, F., Bull, J.M., Cloetingh, S., Scrutton, R.A., 1996. Crustal fault reactivation as initiator of lithospheric folding in the Central Indian Ocean. Geol. Soc. London, Spec. Publ. 99, 251–263.

Beekman, F., Badsi, M., Van Wees, J.D., 2000. Faulting, fracturing and in-situ stress prediction in the Ahnet Basin, Algeria—a finite element approach. Tectonophysics 320, 311–329.

Bond, G.C., Kominz, M.A., 1984. Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky mountains: implications for subsidence mechanisms, age of breakup and crustal thinning. Geol. Soc. Amer. Bull. 95, 155–173.

Bonnet, S., Guillocheau, F., Brun, J.P., 1998. Relative uplift measured using river incision: the case of the Armorican basement (France). C. R. Acad. Sci., Paris, Earth Planet. Sci. 327, 245–251.

Braun, J., 1992. Postextensional mantle healing and episodic extension in the Canning Basin. J. Geophys. Res. 97, 8927–8936.

Brun, J.P., Nalpas, T., 1996. Graben inversion in nature and experiments. Tectonics 15, 677–687.

Burov, E., Cloetingh, S., 1997. Thermomechanical effects of rift shoulder erosion on the evolution of extensional basins. Earth Planet. Sci. Lett. 150, 7–26.

Burov, E., Diament, M., 1995. The effective elastic thickness of continental lithosphere: what does it really mean? (constraints from rheology, topography and gravity). J. Geophys. Res. 100, 3905–3927.

Burov, E.B., Nikishin, A.M., Cloetingh, S., Lobkovsky, L.I., 1993. Continental lithosphere folding in Central Asia (Part II): constraints from gravity and tectonic modelling. Tectonophysics 226, 73–87.

Carter, N.L., Tsenn, M.C., 1987. Flow properties of continental lithosphere. Tectonophysics 136, 63–77.

Cloetingh, S., Burov, E., 1996. Thermomechanical structure of European continental lithosphere; constraints from rheological profiles and EET estimates. Geophys. J. Int. 124, 695–723.

Cloetingh, S., Kooi, H., 1992. Intraplate stresses and dynamical aspects of rift basins. Tectonophysics 215, 167–185.

Cloetingh, S., McQueen, H., Lambeck, K., 1985. On a tectonic mechanism for regional sea level fluctuations. Earth Planet. Sci. Lett. 75, 157–166.

Cloetingh, S., Gradstein, F., Kooi, H., Grant, A., Kaminski, M., 1990. Plate reorganization: a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic? J. Geol. Soc. (Lond.) 147, 495–506.

Cloetingh, S., Sassi, W., Horvath, F., Puigdefabregas, C. (Eds.), 1993. Basin analysis and dynamics of sedimentary basin evolution. Sediment. Geol. 86, pp. 1–201.

Cloetingh, S., d'Argenio, B., Catalano, R., Horvath, F., Sassi, W. (Eds.), 1995a. Interplay of extension and compression in basin formation. Tectonophysics 252, pp. 1–484.

Cloetingh, S., Van Wees, J.D., Van der Beek, P.A., Spadini, G., 1995b. Extension in convergent regimes: constrains from thermo-mechanical modelling of Alpine/Mediterranean Basins and intra-cratonic rifts. Mar. Pet. Geol. 12, 793–808.

Cloetingh, S., Van Balen, R.T., TerVoorde, M., Zoetemeijer, B.P., Den Bezemer, T., 1997. Mechanical aspects of sedimentary basin formation: development of integrated models for lithospheric and surface processes. Geol. Rundsch. 86, 226–240.

Cloetingh, S., Burov, E., Poliakov, A., 1999. Lithospheric folding: primary response to compression? Tectonics 18, 1064–1083.

Cobbold, P.R., Davy, P., Gapais, E.A., Rossello, E.A., Sadybasakov, E., Thomas, J.C., Tondji Biyo, J.J., De Urreiztieta M., 1993. Sedimentary basins and crustal thickening. Sediment. Geol. 86, 77–89.

Dercourt, J., et al., 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamires since the Lias. Tectonophysics 123, 241–315.

Dore, A.G., Lundin, E.R., Birkeland, O., Eliassen, P.E., Jensen, L.N., 1997. The NE Atlantic margin: implications of late Mesozoic and Cenozoic events for hydrocarbon prospectivity. Pet. Geosci. 3, 117–131.

Finetti, I., Bricchi, G., Del Ben, A., Pipan, M., Xuan, Z., 1988. Geophysical study of the Black Sea Basin. Boll. Geofis. Teor. Appl. 30, 197–324.

Gabrielsen, R.H., Strandenes, S., 1994. Dynamic basin development: a complete geoscientific tool for basin analysis. Proc. 14th World Pet. Congr., 13–21.

Gerbault, M., Burov, E., Poliakov, A.N.B., Daignieres, M., 1998. Do faults trigger folding in the lithosphere? Geophys. Res. Lett. 26, 271–274.

Gölke, M., Coblenz, D.D., 1996. Origin of the European regional stress field. Tectonophysics 266, 11–24.

Harland, W.B., Armstrong, R.B., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1990. A Geologic Time Scale. Cambridge Univ. Press, Cambridge, pp. 1–263.

Horvath, F., Cloetingh, S., 1996. Stress-induced late-stage subsidence anomalies in the Pannonian Basin. Tectonophysics 266, 287–300.

Huismans, R.S., Podladchikov, Y.Y., Cloetingh, S., 2001. The transition from passive to active rifting: relative importance of asthenospheric doming and passive extension of the lithosphere. J. Geophys. Res. 106, 11271–11291.

Janssen, M., Stephenson, R.A., Cloetingh, S., 1995. Temporal and spatial correlations between changes in plate motions and the evolution of rifted basins in Africa. Geol. Soc. Amer. Bull. 107, 1317–1332.

Jones, R.W., Simmons, M.D., 1997. A review of the stratigraphy of eastern Paratethys (Oligocene–Holocene) with particular emphasis on the Black Sea. In: Robinson, A. (Ed.), Regional and petroleum geology of the Black Sea and surrounding areas. Am. Assoc. Pet. Geol., Mem. 68, pp. 39–52.

Kohlstedt, D.L., Evans, B., Mackwell, S.J., 1995. Strength of the lithosphere: constraints imposed by laboratory experiments. J. Geophys. Res. 100, 17587–17602.

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

Nikishin, A.M., Cloetingh, S., Lobkovsky, L.I., Burov, E.B., Lankreijer, A.C., 1993. Continental lithosphere folding in Central Asia: Part I. Constraints from geological observations. Tectonophysics 226, 59–72.

Nikishin, A.M., Cloetingh, S., Brunet, M.F., Stephenson, R., Bolotov, S.N., Ershov, A.V., 1998. Scythian platform and Black Sea region: Mesozoic–Cenozoic tectonic and dynamics. In: Crasquin-Soleau, S., Barrier, E. (Eds.), Peri–Tethys Memoir 3: Stratigraphy and Evolution of Peri–Tethyan Platforms. Mem. Mus. Natl. Hist. Nat., Ser. A (Paris) 177, pp. 163–176.

Nikishin, A.M., Ziegler, P.A., Panov, D.I., Nazarevich, B.P., Brunet, M.F., Stephenson, R.A., Bolotov, S.N., Korotaev, M.V., Tikhomirov, P.L., 2001. Mesozoic and Cainozoic evolution of the Scytian Platform–Black Sea–Caucacus domain. In: Ziegler, P.A, Cavazza, W., Robertson, A.H.F., Crasquin-Soleau, S. (Eds.), Peri–Tethys Memoir 6: Peri–Tethyan Rift/Wrench Basins and Passive Margins. Mem. Mus. Natl. Hist. Nat., Ser. A (Paris) 186, pp. 295–346.

Nikishin, A.M., Korotaev, M.V., Ershov, A.V., Brunet, M.F., 2003. The Black Sea Basin: tectonic history and Neogene–Quaternary rapid subsidence modelling. Sediment. Geol., this issue.

Odin, G.S., 1994. Geologic time scale. C. R. Acad. Sci., Paris 318, 59–71.

Okay, A.I., Sengör, A.M.C., Gorur, N., 1994. Kinematic history of the opening of the Black Sea and its effect on the surrounding regions. Geology 22, 267–270.

Ranalli, G., Murphy, D.C., 1987. Rheological stratification of the lithosphere. Tectonophysics 132, 281–295.

Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., Barka, A.A., Kinik, I., Lenk, O., Sanli, I., 1997. Global positioning system measurements of present-day crustal movements in the Arabia–Africa–Eurasia plate collision zone. J. Geophys. Res. 102, 9983–9999.

Robinson, A.G. (Ed.), 1997. Regional and petroleum geology of the Black Sea and surrounding regions. Am. Assoc. Pet. Geol., Mem. 68, pp. 1–385.

Robinson, A., Spadini, G., Cloetingh, S., Rudat, J., 1995. Stratigraphic evolution of the Black Sea: inferences from basin modelling. Mar. Pet. Geol. 12, 821–835.

Rohrman, M., Van der Beek, P.A., Andriessen, P.A.M., Cloetingh, S., 1995. Meso–Cenozoic morphotectonic evolution of Southern Norway: Neogene domal uplift inferred from apatite fission-track thermochronology. Tectonics 14, 704–718.

Smolyaninova, E.I., Mikhailov, V.O., Lyakhovsky, V.A., 1996. Numerical modelling of regional neotectonic movements in the northern Black Sea. Tectonophysics 266, 221–231.

Spadini, G., 1996. Lithospheric deformation and vertical motions in back-arc Mediterranean Basins: the Black Sea and the Tyrrhenian Sea. PhD Thesis, Vrije Universiteit Amsterdam, 152 pp.

Spadini, G., Robinson, A., Cloetingh, S., 1996. Western versus Eastern Black Sea tectonic evolution: pre-rift lithosphere controls on basin formation. Tectonophysics 266, 139–154.

Spadini, G., Robinson, A., Cloetingh, S., 1997. Thermo-mechanical modelling of Black Sea Basin formation, subsidence and sedimentation. In: Robinson, A. (Ed.), Regional and petroleum geology of the Black Sea and surrounding areas. Am. Assoc. Pet. Geol., Mem. 68, pp. 19–38.

Steckler, M.S., Watts, A.B., 1978. Subsidence of the Atlantic-type continental margin off New York. Earth Planet. Sci. Lett. 41, 1–13.

Stephenson, R.A., Cloetingh, S., 1991. Some examples and mechanical aspects of continental lithosphere folding. Tectonophysics 188, 27–37.

Ter Voorde, M., Cloetingh, S., 1996. Numerical modelling of extension in faulted crust: effects of localized and regional deformation on basin stratigraphy. In: Buchanan, P.G., Nieuwland, D.A. (Eds.), Modern developments in structural interpretation, validation and modelling. Geol. Soc. Spec. Publ. 99, pp. 283–296.

Ter Voorde, M., Ravnas, R., Faerseth, R., Cloetingh, S., 1997. Tectonic modelling of the Middle Jurassic synrift stratigraphy in the Oseberg–Brage area, northern Viking graben. Basin Res. 9, 133–150.

Ter Voorde, M., Van Balen, R.T., Bertotti, G., Cloetingh, S., 1998. The influence of a stratified rheology of the lithosphere to (un) loading by extensional faulting. Geophys. J. Int. 134, 721–735.

Van Balen, R.T., Van der Beek, P.A., Cloetingh, S., 1995. The effect of rift shoulder erosion on stratal patterns at passive margins: implications for sequence stratigraphy. Earth Planet. Sci. Lett. 134, 527–544.

Van Balen, R.T., Podladchikov, Y., Cloetingh, S., 1998. A new multi-layered model for intraplate stress-induced differential subsidence of faulted lithosphere, applied to rifted basins. Tectonics 17, 938–954.

Van der Beek, P.A., Cloetingh, S.A.P.L., Andriessen, P.A.M., 1994. Mechanisms of extensional basin formation and vertical motions at rift flanks: constraints from tectonic modelling and fission track thermochronology. Earth Planet. Sci. Lett. 121, 417–433.

Van Wees, J.D., Arche, A., Beijdorff, C.G., Lopez-Gomez, J., Cloetingh, S., 1998. Temporal and spatial variations in tectonic subsidence in the Iberian Basin (eastern Spain): inferences from automated forward modelling of high-resolution stratigraphy (Permian–Mesozoic). Tectonophysics 300, 285–310.

Van Wees, J.D., Beekman, F., 2000. Lithosphere rheology during intraplate basin extension and inversion: inferences from automated modelling of four basins in western Europe. Tectonophysics 320, 219–242.

Van Wees, J.D., Cloetingh, S., 1996. 3D flexure and intraplate compression in the North Sea Basin. Tectonophysics 266, 343–359.

Ziegler, P.A., Cloetingh, S., Guiraud, R., Stampfli, G.M., 2001. Peri–Tethyan platforms: constraints on dynamics of rifting and basin inversion. In: Ziegler, P.A., Cavazza, W., Robertson, A.H.F., Crasquin-Soleau, S. (Eds.), Peri–Tethys Memoir 6: Peri–Tethyan Rift/Wrench Basins and Passive Margins. Mem. Mus. Natl. Hist. Nat., Ser. A (Paris) 186, pp. 9–49.

Ziegler, P.A., Cloetingh, S., Van Wees, J.D., 1995. Geodynamics of intraplate compressional deformation; the Alpine foreland and other examples. Tectonophysics 252, 7–61.

Ziegler, P.A., Van Wees, J.D., Cloetingh, S., 1998. Mechanical controls on collision related compressional intraplate deformation. Tectonophysics 300, 103–129.

Zoback, M.D., Stephenson, R.A., Cloetingh, S., Larsen, B.T., Van Hoorn, B., Robinson, A., Horvath, F., Puigdefabregas, C., Ben-Avraham, Z., 1993. Stresses in the lithosphere and sedimentary basin formation. Tectonophysics 226, 1–13.

Zonenshain, L.P., Le Pichon, X., 1986. Deep basins of the Black Sea and Caspian Sea as remnants of Mesozoic back-arc basins. Tectonophysics 123, 181–211.