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Western versus Eastern Black Sea tectonic evolution: pre-rift lithospheric controls on basin formation

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Abstract

We demonstrate the key role of pre-rift rheology on the kinematics of basin formation in the Western and Eastern Black Sea basins. Constraints on modelling results are provided by a large data-set based on more than 50,000 km of multichannel seismics, offshore and onshore wells, regional gravity and magnetic surveys, refraction seismics and field studies. The model supports the presence of important differences in the thickness and in the thermal state of the lithosphere which rifted to form the Western (middle Barremian) and the Eastern (middle Paleocene) Black Sea subbasins. A 200 km and a 80 km thick pre-rift lithosphere appear to have driven the deformation in the Western and in the Eastern Black Sea, respectively. Differences in the geometry and in the mechanical properties of the pre-rift lithosphere have a strong control on the depth of necking and, thus, on the basin morphology. The model sheds light on palaeotectonic and palaeogeographic reconstructions, duration of rifting events, location of subsiding areas and erosional surfaces. The western and the eastern parts of the Black Sea appear to be two distinct basins, characterised by different evolutionary paths determined by different pre-rift conditions.

Keywords: Black Sea; basin modelling; pre-rift lithosphere; rheology

1. Introduction

Recently, several dynamic modelling studies have emphasised the role of the pre-rift rheology in imposing a particular style of rifting. According to Buck (1991) the pre-rift crustal thickness and the temperature at the base of the crust are likely to be the most effective parameters in driving the deformation to a narrow versus a wide rift. Bassi (1991) and Bassi et al. (1993) validated Buck's conclusions and introduced the importance of considering a wet versus a dry rheology during extension. Other parameters, such as the presence of lithospheric weakness zones (Dunbar and Sawyer, 1989) and strain rate (Kusznir and Park, 1987; Bassi, 1995) have been proposed as factors that have to be taken into account for a better understanding of the rifting processes. Recent work by Cloetingh et al. (1995) determined the key role played by the pre-rift geometries and thermal perturbations in the evolution of a number of Mediterranean and intracratonic basins. In this paper we focus on pre-rift lithospheric geometry and thermal structure, presenting the results of a quantitative basin analysis of the Black Sea. Our kinematic mod-

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elling, its validation through data sets, and the comparison with rheological models, yields constraints on the pre-rift conditions of the lithosphere which rifted to form the eastern and western parts of the Black Sea.

We rationalise the lithospheric thinning, the crustal deformation and the basin formation in the Black Sea area using a numerical modelling approach. In order to chose between different isostatic compensation models, we examine the flexural state of the lithosphere by modelling free-air gravity anomalies along two profiles in each basin parallel to the inferred extension directions. We subsequently test different possible pre-rift lithospheric conditions and different kinematics that could have driven the deformation. To simulate lithospheric and crustal thinning and basin morphology, we use a pure shear model that calculates basement subsidence from defined crustal stretching factors, initial lithospheric thickness and depth of necking (Kooi et al., 1992). We compare the kinematic modelling results with the rheological models of the area affected by the rifting process.

Our modelling study of the Black Sea is based on the following material: (1) a database of more than 50,000 km of multichannel seismics (some reprocessed, some newly acquired in the southeast Black Sea); (2) data from 28 offshore wells and from further onshore wells situated around the Black Sea; (3) extensive field studies in all countries surrounding the Black Sea with the exception of Georgia; (4) regional gravity and magnetic surveys (Robinson et al., 1996); and (5) Russian refraction seismic data (Belousov et al., 1988).

2. Basin configuration and tectonic setting

The Black Sea is located north of Turkey and south of Ukraine and Russia, bordered to the west by Romania and Bulgaria and to the southeast by Georgia (Fig. 1). The general geological setting of the basin has been known for many years (Ross et al., 1974; Letouzey et al., 1977; Zonenshain and LePichon, 1986; Manetti et al., 1988; Okay et al., 1994). Lying towards the northern margin of the group of orogenic belts related to the closure of the Tethys Ocean, the Black Sea is generally considered to be a result of back-arc extension associated with northward subduction of the Tethyan plate. Although this basin is primarily of extensional origin, most of the Black Sea margins are characterised by (and have been modified by) compressive deformation: the Pontides in Northern Turkey and the Greater Caucasus and Gorni Crimea mountain belts in Russia and the Ukraine. Much of the present basin floor is a flat abyssal plain lying at a depth of 2200 m and appears to reflect the presence of a single basin. However, deep reflection seismic studies have shown that there are two extensional basins in the Black Sea which have coalesced in their post-rift phases (Figs. 1 and 2). The Western Black Sea opened with the separation of a fragment including the Western and Central Pontides (North Turkey) from the Moesian Platform (Romania and Bulgaria). Rifting began in the middle Barremian with major post-rift subsidence and probable oceanic crust emplacement in the Cenomanian (Belousov et al., 1988; Finetti et al., 1988; Görür, 1988; Artyushkov, 1992). The post-rift consists of up to 13 km of flat-lying Upper Cretaceous to Recent volcanics and sediments. Rifting in the Eastern Black Sea probably began in the Late Paleocene with rotation of the Mid-Black Sea High away from the Shatsky Ridge–Caucasus (Russia). Extension and probable oceanic crust emplacement were complete by the Middle Eocene (Robinson et al., 1995a) and the Upper Paleocene to Recent post-rift sequence is about 11 km thick.

The older of the two basins, the Western Black Sea, rifted with the dissection of an Upper Jurassic to Lower Cretaceous carbonate platform that had been established on the southern margin (Moesian Platform) of the northern supercontinent, Laurasia. The limestones are as young as middle Barremian in the Western Pontides (Inalte Formation) where they are unconformably overlain by Aptian to Albian syn-rift sediments including shallow-water sandstones, submarine slides and olistostromes and turbidites (Caglayan and Ulus formations). Unconformably overlying the syn-rift strata is a unit of pelagic carbonates and distal tuffs of Cenomanian age (Kapanbogazi Formation) that is interpreted to mark the change from rift to drift in the Western Black Sea (Görür et al., 1993). Seismic reflection data on the Romanian shelf — the conjugate margin to the Western Pontides — shows tilted extensional fault blocks draped by chalks that can be dated as Cenomanian

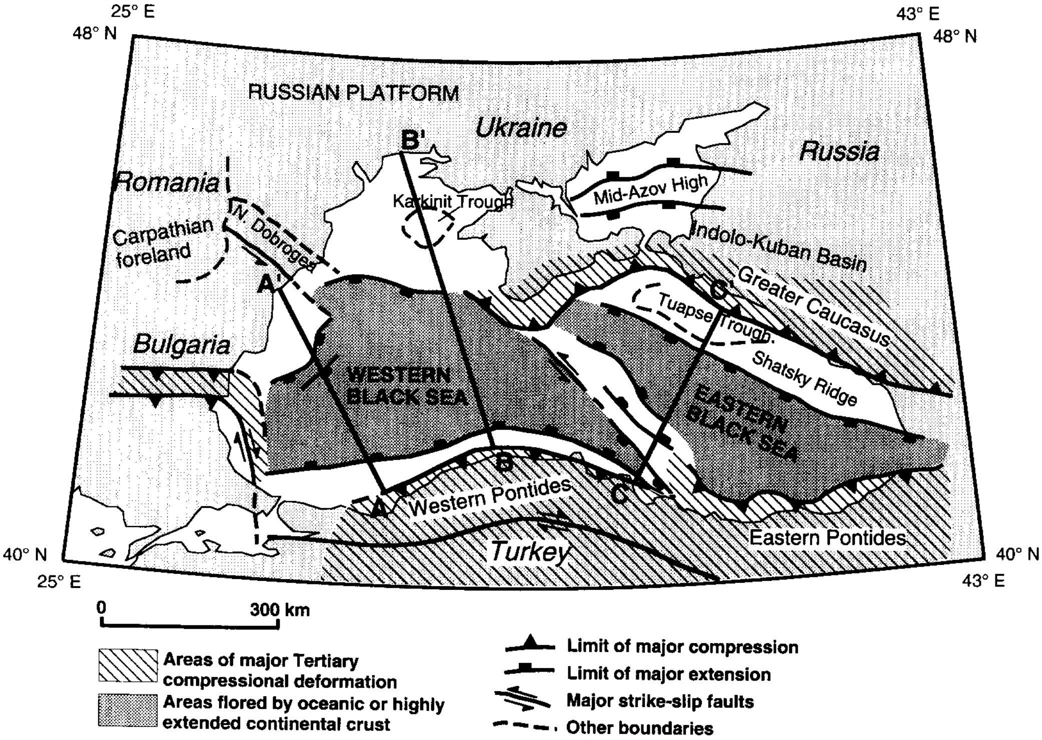

Fig. 1. Location map. The map shows major tectonic elements of the Black Sea area and the locations of the modelled profiles shown in Figs. 5–7.

to Maastrichtian (Robinson et al., 1996). These constraints suggest that rifting took place over a period perhaps as long as 30 m.y. with spreading occupying at most 6–7 m.y. (corresponding to a spreading rate of about 5 cm/year).

The age of the rifting event in the Eastern Black Sea is not as well documented because relevant stratigraphy is poorly exposed. Modelling of seafloor heat flow measurements led Golmshtok et al. (1992) to the conclusion that the basin is Jurassic in age. The presence of a Jurassic marine basin on the southern flank of the Russian Platform is demonstrated by the stratigraphy of the southern slopes of the Greater Caucasus in Russia and Georgia where Sinemurian mudstones unconformably overlie Hercynian metamorphic basement. At least in the Middle Jurassic and Late Cretaceous, this basin lay north of major volcanic arcs exposed now in the Eastern Pontides and can thus be considered to have formed in a back-arc setting. Nonetheless, despite the apparent existence of a Jurassic to Cretaceous back-arc basin, three lines of evidence suggest that the Eastern Black Sea in its present form rifted after the Early Paleocene (Danian). Firstly, the uppermost part of what offshore seismics clearly shows to be the pre-rift — the Shatsky Ridge (northern rift shoulder) — has been drilled by numerous petroleum exploration wells in Georgia (e.g., Ochamchire) and shown to be a thick Mesozoic sequence including Middle Jurassic volcanics and volcanoclastic sediments, Upper Jurassic to Lower Cretaceous limestones (locally with evaporites) and an apparently complete Upper Cretaceous to Danian sequence of turbidites and chalks. These are overlain unconformably by Upper Eocene mudstones. The same stratigraphic relationship has been found on dredging the seafloor north of the Turkish coast where the conjugate margin of the rift, the Archangelsky Ridge (Mid-Black Sea High) outcrops on the seafloor (Rudat and Macgregor, 1993): Upper Cretaceous volcanics, tuffs and chalks including tuffaceous material are overlain unconformably by Eocene mudstones. Finally, the Upper Paleocene

Fig. 2. Free-air gravity map of the Black Sea and location of the profiles analysed by our gravity modelling procedure (Figs. 3 and 4). Colours indicate values from 230 mGal (bright pink) to −100 mGal (dark blue). See also Figs. 3 and 4 for free-air gravity anomaly values along the modelled profiles.

is missing in the Eastern Pontides (Robinson et al., 1995a). Dating of the deepest parts of the post-rift fill suggests that spreading in the Eastern Black Sea was completed by the Middle Eocene (Robinson et al., 1996). In summary, in contrast to the situation in the Western Black Sea where the stable Moesian Platform was rifted, rifting in the eastern basin apparently superimposed a younger (Paleocene) extensional basin on an area that had already been a back-arc basin since the Early Jurassic. The maximum length of time available for opening of the Eastern Black Sea is thus around 11 m.y.

The structure of the crust beneath the Black Sea has been determined by refraction seismic profiling (Belousov et al., 1988; Neprochnov et al., 1974). Beneath the Western Black Sea, the Moho rises from a depth of 45 km beneath the Pontides mountain belt to around 20 km in the centre of the Western Black Sea, falling again to the north, to a depth of 40–45 km beneath the Russian Platform. The post-rift fill in the Western Black Sea is as deep as 15 km in the basin centre and the crust has a thickness characteristic of oceanic crust. Beneath the Eastern Black Sea, the Moho rises to about 25 km. The base of the post-rift lies at a depth of about 13 km, suggesting that the crust in the Eastern Basin may not be entirely oceanic. The evidence for well developed magnetic anomalies is absent. This may be due in part, in the western basin, to the coincidence of spreading with the Late Cretaceous quiet zone but, in both basins, could be largely due to the obscuring effect of the huge thickness of post-rift sediments.

In the Early Cretaceous, the crust beneath the location of the rift that was to become the Western Black Sea was part of the Moesian–European Platform with a characteristic crustal thickness of around 35 km. It is possible that crust along this southern margin of Laurasia had been thickened during the Middle Jurassic Cimmerian Orogeny (Sengör et al., 1980, 1984, 1988; Ustaömer and Robertson, 1994) but the deposition of shelf carbonates during the Late Jurassic and Early Cretaceous (a period of around 35 Ma) suggests stabilisation of the region. Rifting in the Eastern Black Sea affected Russian Platform crust with characteristic thickness of 40–45 km (Guterch et al., 1986). However, as the area was already a basin by the time of rifting initiation, the crust may have been previously thinned.

3. Lithospheric state of flexure: constraints by gravity modelling

The tectonic evolution of extensional basins depends on the isostatic compensation of the vertical loads acting on a stretched and thinned lithosphere. Loads resulting from crustal thinning, thermal contraction and basin fill can be compensated regionally or locally depending on the capability of the lithosphere to distribute these loads over a broad area. The rigidity of the lithosphere is the key parameter controlling the flexural behaviour of a deforming plate. Predictions on basin architecture and subsidence patterns have to take into account these different mechanisms of load compensation since they strongly control the effects of thinning and stretching operating on the lithosphere (Kooi et al., 1992; Spadini et al., 1995). A kinematics of extension leading to the formation of an overdeep basin (deeper than an isostatic compensated situation) would cause an upward state of flexure; if an underdeep basin is formed, a downward state of flexure is expected (Braun and Beaumont, 1989; Weissel and Karner, 1989; Kooi et al., 1992). Braun and Beaumont (1989) and Kooi (1991) showed that a deep level of necking (the lithospheric level with no vertical movements during deformation in absence of restoring forces) creates an overdeep surface depression and an upward vertical load is expected in order to restore the isostatic equilibrium. Conversely, a shallow level of necking creates an underdeep surface depression and a downward compensating vertical load. The understanding of the state of lithospheric flexure is important for modelling predictions on basin fill. The depths of necking (or local isostasy) and their states of flexure are not apparent from the shape of the basin but they have an important expression in the gravity signal (Fig. 2), especially in the 'isostatic residual anomaly' (Kooi, 1991). The isostatic residual anomaly is defined as the difference between the observed (free-air) anomaly and the anomaly predicted if the basin was compensated locally ('isostatic anomaly'). A positive isostatic residual anomaly indicates overcompensation and a negative isostatic residual anomaly indicates undercompensation. Upward flexure, related to a deep level of necking, is associated with overcompensated basin flanks and an undercompensated basin centre;

downward flexure and a shallow level of necking are expressed by undercompensated basin flanks and an overcompensated basin centre.

We performed gravity modelling of the Western and of the Eastern Black Sea subbasins along two transects (Fig. 2) applying a 2-D forward and inverse numerical model that is able to simulate the gravity anomaly signature produced by a given distribution of mass. The inversion program models a structural cross-section as an ensemble of 2-D prisms formed by linking vertices into a network that may be deformed by a modified Marquardt algorithm. The non-uniqueness of the solution of this approach is solved by a trial and error procedure. Geometry and densities of large-scale bodies have been defined by the combination of seismic reflection and refraction data (Belousov et al., 1988; Finetti et al., 1988). A velocity–density conversion based on the Nafe–Drake curve (Ludwig et al., 1970), allows us to assign a density of 2700 kg m^{-3} and 2980 kg m^{-3} to the upper and the lower crust, respectively. For the heavily thinned crust underlying the central areas of the basin, the density has been constrained by refraction seismic at 2900 kg m^{-3} in the west (possible basaltic layer) and at 2800 kg m^{-3} in the east. The thick sedimentary cover of the Black Sea has been approximated, with a number of horizontal layers (according to seismic data available for the west and for the east) with densities ranging from 2000 kg m^{-3} to 2600 kg m^{-3}. Seismic velocities indicate a density of 3330 kg m^{-3} of the mantle underlying both the Western and the Eastern Black Sea crust.

We have calculated the isostatic anomaly and the isostatic residual anomaly along two transects, in the Western Black Sea (WBS) and in the Eastern Black Sea (EBS), based on a high-quality regional gravity data set (Fig. 2). Both in the Eastern and Western Black Sea, a clear discrepancy exists between the observed and the isostatic anomaly indicating a non-local isostatic compensation of the Black Sea lithosphere (Figs. 3 and 4). The large wavelength of the residual anomaly indicates that the discrepancy cannot be due to small-scale density variations that are not included in our calculation, but reflects a regional feature.

The analysis of the sign of the isostatic residual anomaly (Figs. 3 and 4) reveals an interesting and pronounced difference between the Eastern and the Western Black Sea basins. The Western Black Sea appears to be in an overall upward state of flexure (undercompensated basin centre and overcompensated basin flanks) and the Eastern Black Sea in a downward state of flexure (overcompensated basin centre and undercompensated basin flanks). This suggests that the level of necking involved in the deformation is deep in the west but shallow in the east.

Using an inverse gravity modelling procedure we have also calculated the 'best-fit Moho', the Moho that gives the best-fit with the observed free-air anomaly signature. The relation between the best-fit Moho and the isostatic Moho (Figs. 3 and 4) also shows a constant pattern: the best-fit Moho is the deepest below the basin flanks and shallowest below the basin centre for the Western Black Sea. The opposite is true in the Eastern Black Sea. Again a deep level of necking is expected for the west and a shallow one for the east. The refraction Moho generally follows the best-fit Moho (in the sense that it has the same geometrical relationship with the isostatic Moho) with some important exceptions. In the Western Black Sea between km 270 and km 340 (Fig. 3) along the analysed transect we predict a much deeper Moho than detected by refraction seismics (Belousov et al., 1988). This difference does not alter our conclusions since it is confined to a relatively small area and it is probably the product of a small-scale density contrast within the crust. The central portion of the Eastern Black Sea (between km 130 and km 230) (Fig. 4) is characterised by a predicted Moho shallower than the seismically defined base of the crust. The shallow Moho (related to the broad positive free-air anomaly at the basin centre) is responsible for the overcompensation of the area. A shallower Moho at the basin centre seems to be likely to occur since the positive free-air anomaly is a large 3-D feature characterising the whole central part of the Eastern Black Sea (Fig. 2). The refraction seismic studies could have overestimated the depth of the Moho. This would support the presence of oceanic crust in the Eastern Black Sea, instead of continental stretched crust. This interpretation could have a strong effect on estimates for crustal thinning.

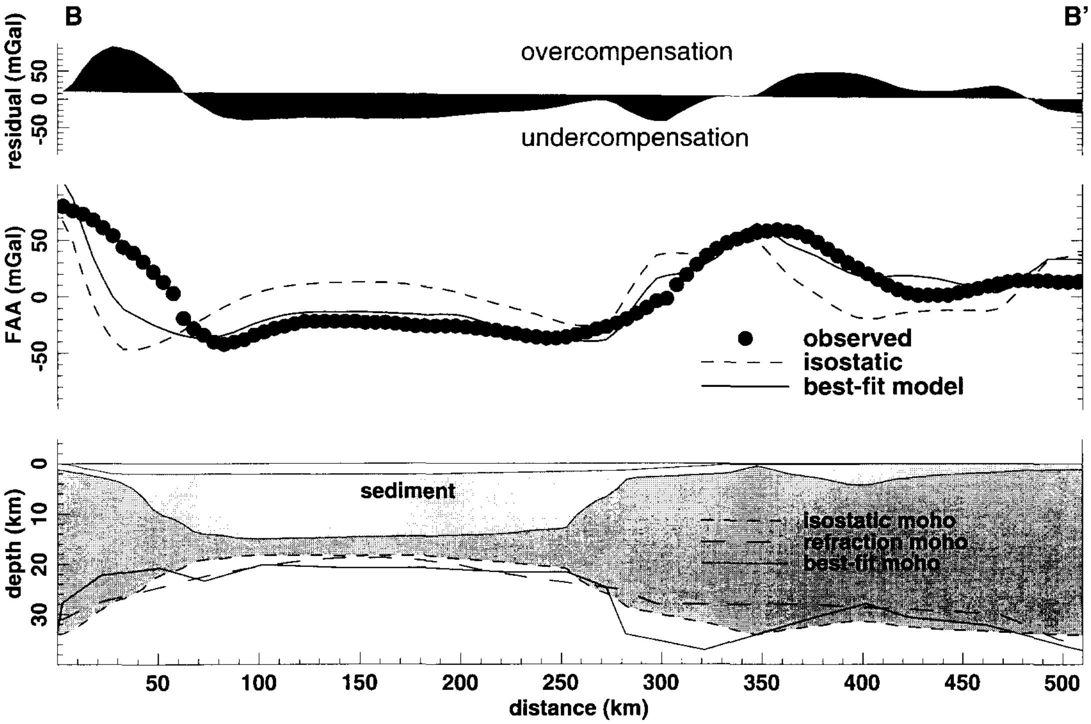

Fig. 3. Gravity and state of flexure in the Western Black Sea (*B–B'* in Figs. 1 and 2). The figure illustrates the method of calculating the residual gravity anomaly (the difference between the observed free-air gravity anomaly and the anomaly that would be produced if the basin was locally isostatic compensated). The deviation (residual anomaly) from a local isostatic compensation is a measure for the state of flexure of the lithosphere. An upward state of flexure is suggested for the Western Black Sea. Also shown is the Moho shape which provides the best fit with the measured gravity anomalies.

4. Tectonic modelling

We modelled the Black Sea basin tectonic evolution applying a finite difference kinematic model of lithospheric thinning (Kooi et al., 1992). We take into account the finite duration of a non-adiabatic rifting and a non-zero strength of the lithosphere which can compensate changing loads in a regional manner. The flexural rigidity of the lithosphere is controlled by the effective elastic thickness (EET) that we consider temperature dependent and being defined as the depth to the 400°C isotherm (Watts et al., 1982). The complete set of parameters we use in the model is given in Table 1. We also take into account the presence of a level of necking (Kooi et al., 1992) in order to simulate the dynamic control of a specified lithospheric layer on the kinematics of extension and thinning (Spadini et al., 1995). The state of lithospheric flexure and the imprinting of the necking-related thinning are also taken into account for predictions during the post-rift thermal cooling and subsidence. We simulate the presence of oceanic crust in the Western Black Sea, using the concept of a limited β-factor, a value beyond which stretching will be superseded by creation of new oceanic lithosphere. Following Keen and Beaumont (1990) we use a β-factor of 5.5 as a reasonable approximation to simulate oceanic thermal subsidence when a uniform extension model is used.

The analysed transects (Figs. 5–7) are divided in a finite number of boxes for which we assign thinning factors. Crustal thinning factors (β) along the three profiles are calculated from the depth converted reflection seismics (pre-rift basement morphology), the Moho depth determined by refraction seismics (Belousov et al., 1988) and initial crustal thicknesses (taken to be 35 km for both basins). As discussed above, we are aware that the refraction seismic ex-

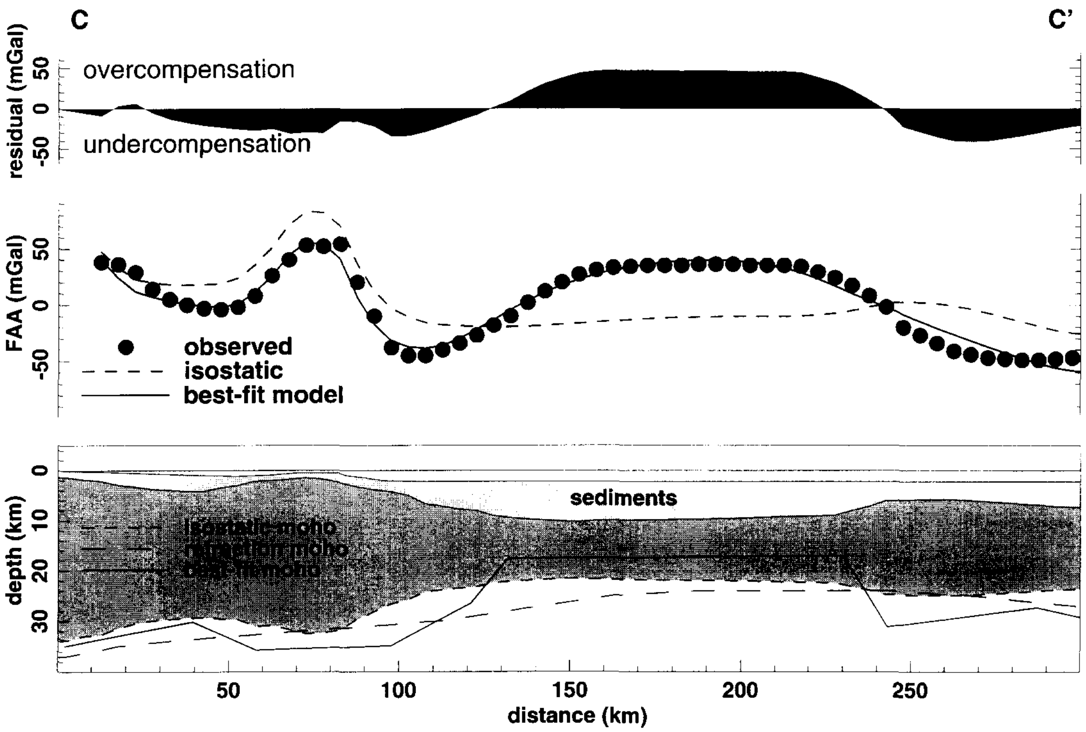

Fig. 4. Results of gravity modelling for the Eastern Black Sea suggesting a downward state of flexure. The best-fit Moho ('gravity Moho') is much shallower than the Moho defined by refraction seismic.

periments can contain errors in estimating the position of the base of the crust. The choice of using the refraction-defined Moho to estimate thinning factors was driven by the need for a consistency that would permit comparisons between different scenarios (i.e., different initial lithospheric thicknesses, different depths of necking during extension). The thickness of crust prior to rifting and the derived thinning factors influence the predicted syn-rift subsidence. In our model the base of the lithosphere is considered to be controlled by the 1333°C isotherm. The initial lithospheric thickness has also a strong influence in limiting the syn-rift subsidence: if the ratio between initial crustal thickness and initial lithospheric thickness is smaller than about 0.15 no subsidence takes place, it will be superseded by uplift (McKenzie, 1978). The depth of necking defines the layer where vertical movements are compensated by horizontal shear; it directly controls the syn-rift subsidence of the basin and its morphology. Neither initial lithospheric thickness nor depth of necking are known a priori. We, therefore, consider a 'cold' (200 km thick), an 'intermediate' (120 km) and a 'warm' (80 km) pre-rift lithosphere in order to investigate the role played by the subcrustal thinning in the vertical

Table 1
Model parameters

	Value	Definition
T_c	400°C	Isotherm describing EET
T_0	0°C	Surface temperature
T_a	1333°C	Asthenosphere temperature
k	7.8×10^{-7} m^2 s^{-1}	Thermal diffusivity
α	3.4×10^{-5}°C	Thermal expansion coefficient
g	9.8 m s^{-2}	Gravitational acceleration
ρ_c	2800 kg m^{-3}	Surface density crustal rock
ρ_m	3330 kg m^{-3}	Surface density mantle rock
ρ_s	2700 kg m^{-3}	Sediment grain density
ρ_w	1030 kg m^{-3}	Water density
ϕ_0	0.55	Sediment surface porosity
c	0.55 km^{-1}	Compaction depth constant

EET = effective elastic thickness.

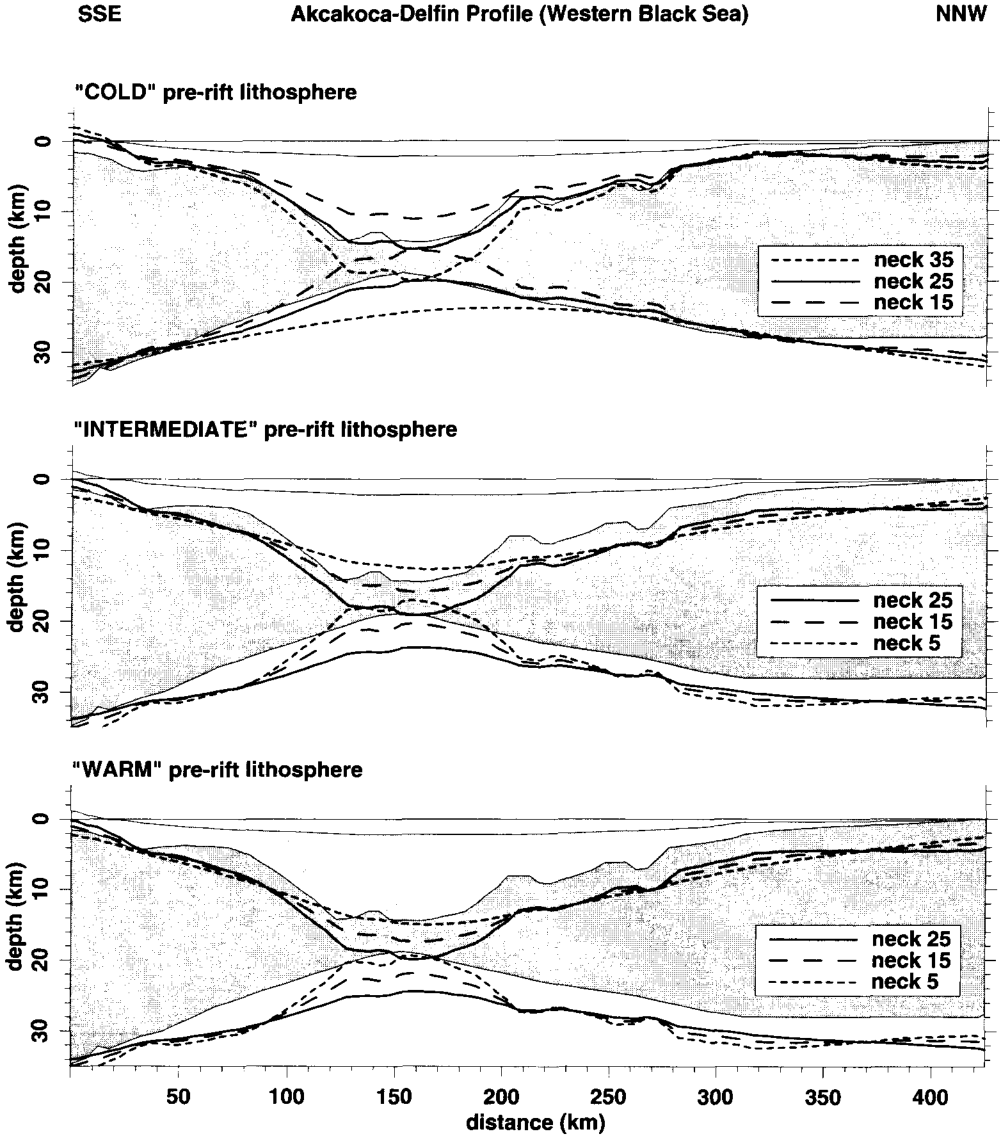

Fig. 5. Profile *A–A'*. Crustal configurations predicted for different pre-rift lithospheric geotherms along the profile *A–A'* (Fig. 1) in the Western Black Sea. The base of the lithosphere (1333°C) is fixed at 200 km depth in the 'cold' model, 120 km in the 'intermediate' and 80 km in the 'warm' model. Also shown is a sensitivity test on different depths of necking adopted. A cold and thick lithosphere prior to rifting and a medium-deep depth of necking (25 km) yield the best fit with the observed crustal geometry (darker grey in the figure). Observed sediment thickness in light grey.

movements. We also present a sensitivity test on the different depths of necking adopted.

The two sections in the Western Black Sea (*A–A'* and *B–B'*) (Figs. 5 and 6) run SSE–NNW (Fig. 1), aligned along the direction of extension. The western section (*A–A'*) runs from the offshore exploration well Akcakoca-2 through the deep post-rift basin and onto the relatively little extended Moesian Platform of the Romanian shelf. The eastern section (*B–B'*) runs from the Turkish town of Cide again into the post-rift basin, across the Kalamit Ridge and Karkinit Trough and onto the southern margin of

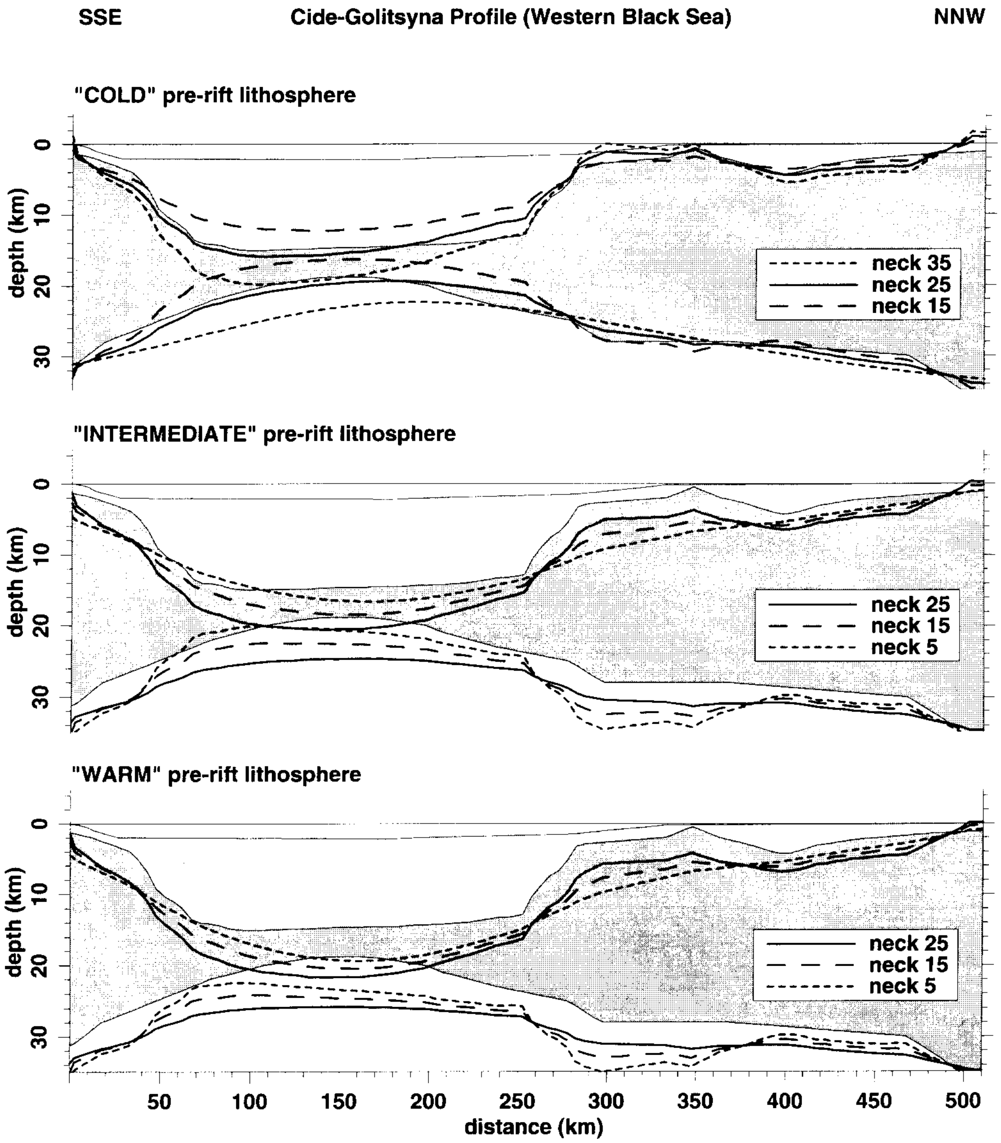

Fig. 6. Crustal configurations predicted for different pre-rift lithospheric geotherms along the profile *B–B′* (Fig. 1) in the Western Black Sea. The base of the lithosphere (1333°C) is fixed at 200 km depth in the 'cold' model, 120 km in the 'intermediate' and 80 km in the 'warm' model. Also shown is a sensitivity test on different depths of necking adopted. A cold and thick lithosphere prior to rifting and a medium-deep depth of necking (25 km) give the best fit with the observed crustal geometry. Figure conventions as in Fig. 5.

the Russian Platform in the Gulf of Odessa (Fig. 1). The section that we model in the Eastern Black Sea (*C–C′*) (Fig. 7) is aligned SSW–NNE, again parallel to the inferred extension direction (Fig. 1). This section runs from the Badut petroleum exploration well in North Turkey towards the town of Gelendzhik on the Russian coast, crossing the Sinop Trough, Archangelsky Ridge, Eastern Black Sea basin and Shatsky Ridge (Fig. 1). The profile was truncated short of the Russian–Georgian coastline to avoid the shortening and crustal thickening associated with the Caucasus mountain belt.

4.1. Pre-rift crustal and lithospheric thicknesses and depth of necking

Figs. 5–7 show bathymetry, the mapped top of the pre-rift basement and the position of the Moho (Belousov et al., 1988) for each of the three modelled sections. As discussed above, the thickness of the crust prior to rifting in the two basins is difficult to know because of the long and complex tectonic history of the region. For crustal thicknesses of 40

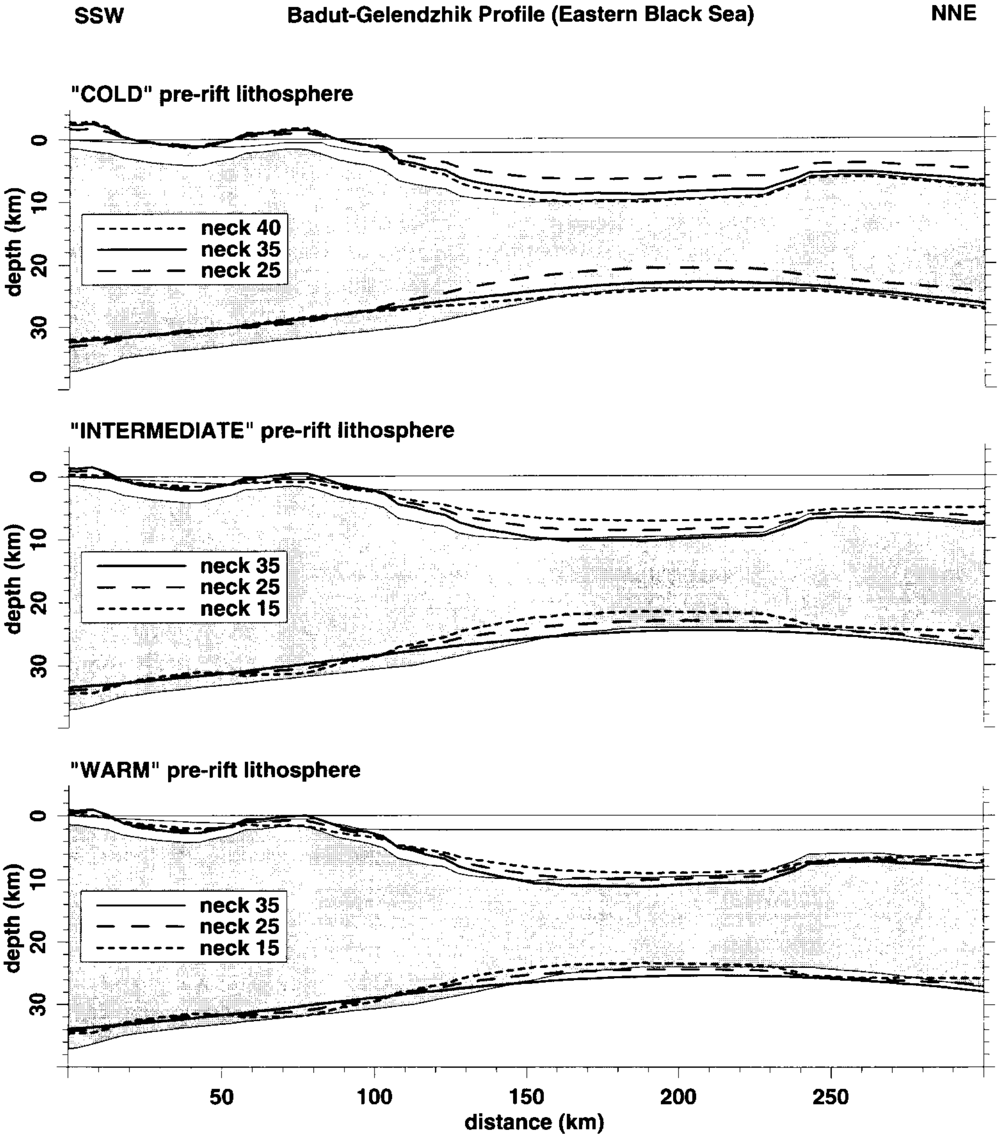

Fig. 7. Crustal configurations predicted for different pre-rift lithospheric geotherms and depths of necking along the profile *C–C′* (Fig. 1) in the Eastern Black Sea. The base of the lithosphere (1333°C) is fixed at 200 km depth in the 'cold' model, 120 km in the 'intermediate' and 80 km in the 'warm' model. A warm and thin lithosphere prior to rifting gives the best fit with the observed crustal geometry. The predicted configuration is not very sensitive to different depths of necking within the 'warm scenario'. Although the tectonic model cannot discriminate among the different values of depth of necking tested, the result of the gravity modelling (Fig. 4) suggests a shallow level of necking. Figure conventions as in Fig. 5.

and 45 km, the predicted relative amount of syn-rift subsidence is substantially increased, for which feature there is very little evidence on seismic profiles (Robinson et al., 1995b). As a result, an initial thickness of 35 km was adopted for the modelling of both basins.

Also shown in Figs. 5–7 are modelled crustal configurations calculated using initial lithospheric thicknesses of 80, 120 and 200 km. In the Eastern Black Sea, the best fit to the observed crustal geometry along the *C–C′* section is for an initial lithospheric thickness of 80 km (Fig. 7). The 'warm' model appears to provide the best fit but the differences with the 'intermediate' scenario are very small and they are probably within the error range of the observed data. For the modelled sections *A–A′* and *B–B′* the situation is quite different (Figs. 5 and 6). With an initial lithospheric thickness of 80 km, there is a large mismatch between predicted and observed crustal structure and the best fit is obtained for a 200 km thick (cold) lithosphere. This result is very robust since the differences between the cold and the warm model are large not only on the margins, where boundary conditions not taken into account in our modelling (i.e., loads from the Pontides orogenic belt) can play a substantial role, but along the entire transect.

Our calculations show an inverse relationship between pre-rift lithospheric temperature and sensitivity to the depth of necking selected. In the Eastern Black Sea, where a warm lithosphere is inferred, it is therefore difficult to select the most appropriate position of the necking level. The gravity modelling, nonetheless, shows that a relatively shallow depth of necking has to be preferred (15 km). In the Western Black Sea, the best-fit model for the *A–A′* and *B–B′* profiles provides a well constrained estimate on the depth of necking: a lower crustal layer (25 km) clearly controls the rifting-related thinning and the flexural response of the lithosphere. The differences in predicted pre-rift basement depth between the best-fit model (25 km depth of necking) and the other scenarios vary between 2 and 6 km at the centre of the basin (Figs. 5 and 6). These discrepancies are much higher than any possible error in the observation; this makes the conclusion very robust.

5. Implications for the Black Sea lithosphere evolution

The model results support the existence of a consistent and substantial difference in the nature of the lithosphere which rifting led to the formation of the Western Black Sea in the Middle Cretaceous and the Eastern Black Sea in the Paleocene. The Western Black Sea was initiated on a cold, thick lithosphere (200 km), the Eastern Black Sea on a warm, thin lithosphere (80 km). Besides this difference in the implied lithospheric thickness, the extension in the Western Black Sea appears to be controlled by a deep crustal level of necking (25 km) whereas in the Eastern Black Sea, the inferred level of necking is shallow (15 km). This controls the state of flexure of the deformed lithosphere and explains the differences in the gravity field over the studied area.

Differences in the lithospheric depth of necking during extension suggest different mechanical properties characterising the Eastern and the Western Black Sea lithosphere before and during rifting (Kooi et al., 1992; Cloetingh et al., 1995; Spadini et al., 1995). In fact, the geometry and the thermal state of the pre-rift lithosphere (that ultimately control its dynamic response) are likely to impose different evolutionary paths on the deforming plate. To investigate the possible dynamic constraints on the kinematic evolution we calculate the strength profiles that should have characterised the Western and the Eastern Black Sea lithosphere at the beginning of rifting (Fig. 8). We adopt different lithospheric thicknesses and geotherms according to the results of the tectonic modelling. Strain rate in the west (2.2×10^{-15} s^{-1}) and in the east (4.9×10^{-15} s^{-1}) were derived from the averaged value of thinning factors on continental lithosphere and from the duration of rifting. Strength profiles based on extrapolation of rock-mechanics data (Carter and Tsenn, 1987) (Fig. 8) suggest a pronounced difference in the mechanical properties of the pre-rift lithosphere between the Western Black Sea and the Eastern Black Sea that could have strongly controlled the overall kinematics of rifting. In the Western Black Sea the inferred strength distribution localises the depth of necking either at deep crustal levels (combined effects of the upper mantle and crustal strength, the 'strong couple'; Spadini et al., 1995) or below the

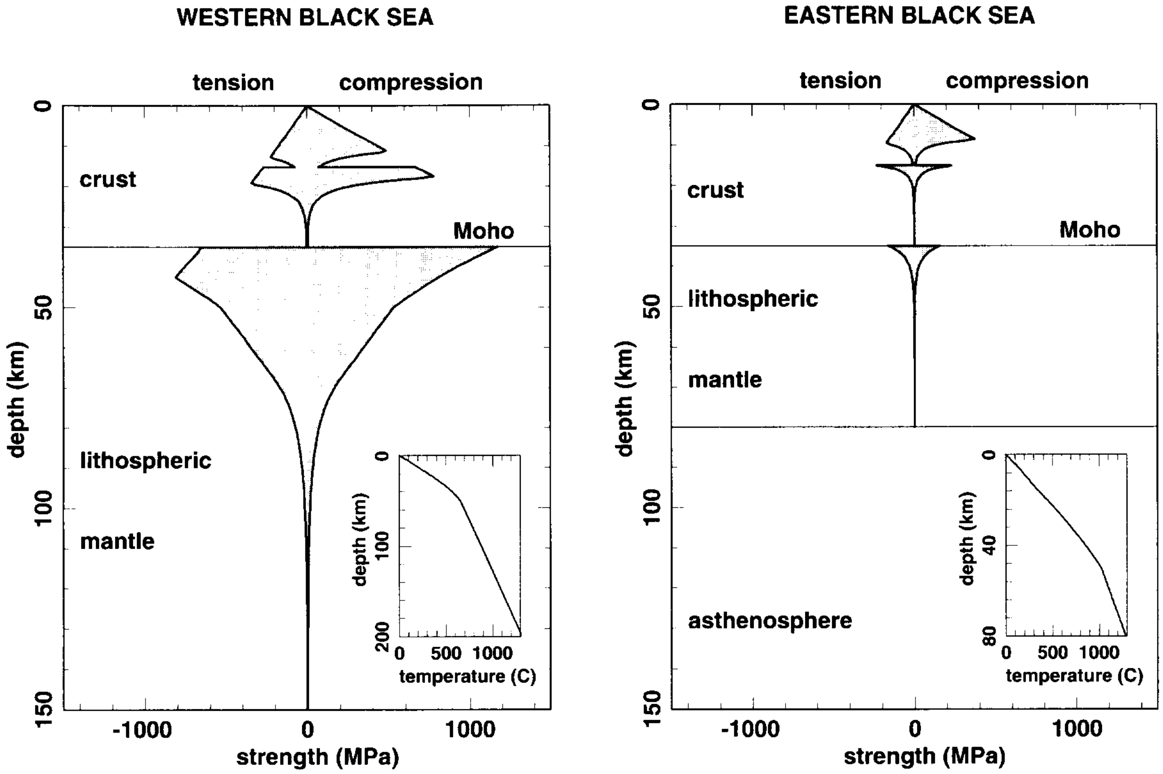

Fig. 8. Strength vs depth for a layered rheology (granite, diorite, olivine for the upper crust, lower crust, and mantle, respectively; Banda and Cloetingh, 1992) calculated for the Western Black Sea (WBS) and for the Eastern Black Sea (EBS) at the beginning of rifting. For the calculation we use the best-fit geotherms (inset) derived by tectonic modelling. Strain rate in the west (2.2×10^{-15} s^{-1}) and in the east (4.9×10^{-15} s^{-1}) were derived from the averaged value of thinning factors on continental lithosphere and from the duration of rifting. The strength profiles for the lithosphere are based on extrapolation of rock-mechanics data (Carter and Tsenn, 1987). Note that the higher strain rate adopted for the EBS should increase the strength of the ductile layers (e.g., upper mantle). In reality, in this case, the strength is mainly controlled by the different geotherms adopted; the EBS lithosphere appears to be much weaker than the WBS lithosphere. Levels of necking predicted through tectonic modelling for the WBS and for the EBS are also shown (horizontal line in light grey).

Moho (key role played by the strong upper mantle) (Kooi et al., 1992). The first hypothesis seems the most appropriate after the comparison of the strength distribution with depth with the best-fit value (25 km) obtained for the depth of necking. In the Eastern Black Sea, the inferred warm state of the lithosphere predicts a very weak mantle: shallow to mid-crustal crustal layers are likely to impose the style of rifting around a shallow level of necking, as confirmed by gravity and tectonic modelling results.

The proposed model (see also Fig. 9) involving rifting of mechanically different lithospheres in east and west, is supported by several features of the initiation and development of the Eastern and the Western Black Sea basins.

5.1. Geological setting prior to rifting

The existence of two very different types of lithosphere in the Black Sea region prior to rifting is supported by palaeogeographic reconstructions (Robinson and Banks, 1995). The Western Black Sea developed on the stable continental Moesian Platform in a setting generally considered to be 'back-arc' but without any contemporaneous volcanics. The lithosphere in this case would be expected to be both thick and cold. In contrast, the Eastern Black Sea developed on a pre-existing back-arc basin, north of an Upper Cretaceous (and a later Eocene) volcanic arc. The lithosphere in this case would be expected to be both thin and warm.

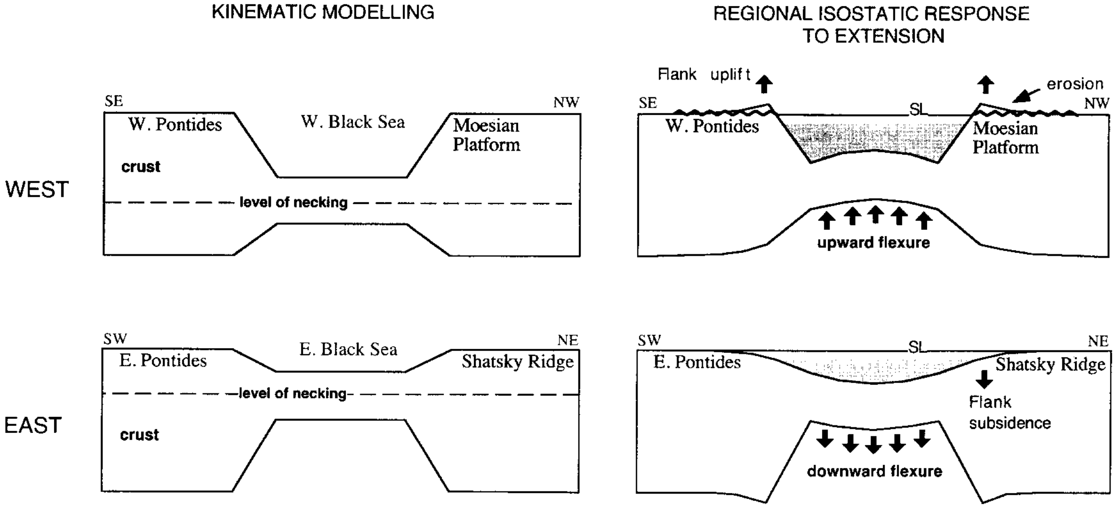

Fig. 9. Cartoon illustrating a scenario for the large-scale deformation of the Black Sea basin and the surrounding regions. Our reconstruction is consistent with several observed geological features of the present-day Black Sea and explains different aspects of its tectonic evolution. See discussion in the text.

5.2. Rift flank uplift, overall subsidence and duration of rifting

One of the features predicted for a rift initiated on thick cold and, therefore, strong lithosphere (such as the Western Black Sea) is a substantial associated flank uplift, a result primarily of the high flexural rigidity of the plate (Fig. 9). This tends to produce major rift flank erosion. Such erosion is in fact observed in the Western Pontides where the latest pre-rift strata — Upper Jurassic to Neocomian limestones — were eroded, karstified and in places completely removed prior to the Aptian. In contrast, the flanks of rifts initiated on hot, warm and therefore weak crust (such as the Eastern Black Sea) tend to subside. Seismic lines across the Shatsky Ridge — the northern rift flank of the Eastern Black Sea — show no evidence for syn-rift erosion (Robinson et al., 1996).

Basins developed on thick lithosphere involving a larger depth of necking tend to undergo more total subsidence. This provides an explanation for why the Western Black Sea has a thicker sedimentary fill than the Eastern Black Sea.

Marginal rift basins developed on a thick lithosphere appear to generally rift over longer periods than basins developed on thin lithosphere (Cloetingh et al., 1995). Ultimately, the integrated strength of the lithosphere seems to have an important role in controlling the duration of rifting. The strong Western Black Sea lithosphere (Fig. 8) apparently rifted for about 30 m.y. while rifting and spreading in the Eastern Black Sea, characterised by a much weaker lithosphere (Fig. 8) were completed within 8 m.y.

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