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HEINEMANN

Marine and Petroleum Geology, Vol. 12, No. 8, pp. 821–835, 1995
Elsevier Science Ltd
Printed in Great Britain
0264-8172/95 $10.00 + 0.00

Stratigraphic evolution of the Black Sea: inferences from basin modelling

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Received 30 September 1994; revised 10 February 1995; accepted 9 May 1995

A modelling simulation of the syn-rift and post-rift stratigraphies and subsidence history of the Western and Eastern Black Sea basins is described. The model uses the initial lithospheric conditions and rifting parameters (thinning factors, effective elastic thickness and depth of necking) derived by large-scale lithospheric deformation modelling. Using a stratigraphic modelling approach, supported by a large and high-quality data set, constraints on the palaeowater depth evolution of the basin and associated basement subsidence are provided. The model reproduces and provides explanations for several features of the stratigraphy of the Black Sea: the apparent near-absence of syn-rift strata (other than in the Western Pontides); thin to condensed early post-rift sequences in both basins; a thick Upper Eocene sequence in the Eastern Black Sea; a relatively thin Oligocene to Miocene sequence and a very thick Quaternary sequence. It also predicts the geometry and depth of the lake that developed in the centre of the Black Sea when the sea level fell by 1500 m during the Late Miocene.

Keywords: basin modelling; basin subsidence; Black Sea

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 south-east by Georgia (*Figure 1*). It is linked to the Mediterranean by the Bosporus, Sea of Marmara and Dardanelles and currently contains water of below normal salinity, a result of restricted exchange with the oceans and of the large freshwater input from major rivers such as the Dnieper and the Danube (Ross *et al.*, 1974). The general geological setting of the Black Sea has been known for many years (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, it is generally considered to be a result of back-arc extension associated with northward subduction of the Tethyan plate to the south. Thus the Black Sea is primarily of extensional origin, even though most of its margins are characterized 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 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 (*Figure 1*). 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 (Finetti *et al.*, 1988; Görür, 1988). The post-rift consists of up to 13 km of largely flat-lying Upper Cretaceous to Recent volcanics and sediments. Rifting in the Eastern Black Sea probably began in the Late Palaeocene with rotation of the Mid-Black Sea High (Andrusov and Archangelsky ridges) away from the Shatsky Ridge–Caucasus (Russia). Extension and probable oceanic crust emplacement were complete by the Middle Eocene (Robinson *et al.*, in press) and the Late Palaeocene to Recent post-rift is around 11 km thick.

Spadini *et al.* (in press) modelled the crustal deformation and the basin formation of the Western and Eastern Black Sea basins and drew conclusions about the nature of the lithosphere that rifted to form the two basins. In this paper, we model the post-rift stratigraphic development of the basins in an attempt to

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explain variations in sedimentation rates (thicknesses) and facies. Firstly, we discuss the nature, ages and durations of the two rifting events that produced the eastern and western basins. We then describe the main features of the Black Sea post-rift, explaining how the intervals were mapped using reflection seismic data and pointing out the major features of the stratigraphic record that require explanation. This description of the Black Sea is based on mapping of more than 50 000 km of multichannel seismic data (some reprocessed, some newly acquired in the south-east Black Sea), data from 28 offshore wells and from further onshore wells situated around the Black Sea, extensive field studies in all countries surrounding the Black Sea with the exception of Georgia and regional gravity and magnetic surveys (Robinson *et al.*, in press). We then describe how the model works, its results and their implications for understanding the subsidence history and the stratigraphic development of the Black Sea basins.

Rifting of the Black Sea basins

The older of the two basins is the Western Black Sea. Rifting began 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 (İnaltı Formation), where they are unconformably overlain by Aptian to Albian syn-rift sediments including shallow water sandstones, submarine slides and olistostromes and turbidites (Çağlayan and Ülüs Formations). Unconformably overlying the syn-rift strata is a unit of pelagic carbonates and distal tuffs of Cenomanian age (Kapanboğazı Formation), which is interpreted to mark the change from rift to drift in the Western Black Sea (Görür *et al.*, 1993). Reflection seismic data on the Romanian shelf — the conjugate margin to the Western Pontides — show tilted extensional fault blocks draped by chalks. The chalks can be dated from ties to Romanian oil exploration wells as Cenomanian to Maastrichtian (Robinson *et al.*, in press).

The age of the rifting event in the Eastern Black Sea is not as well documented because the 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 confirmed 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 now exposed 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 Palaeocene (Danian). Firstly, the uppermost part of what offshore

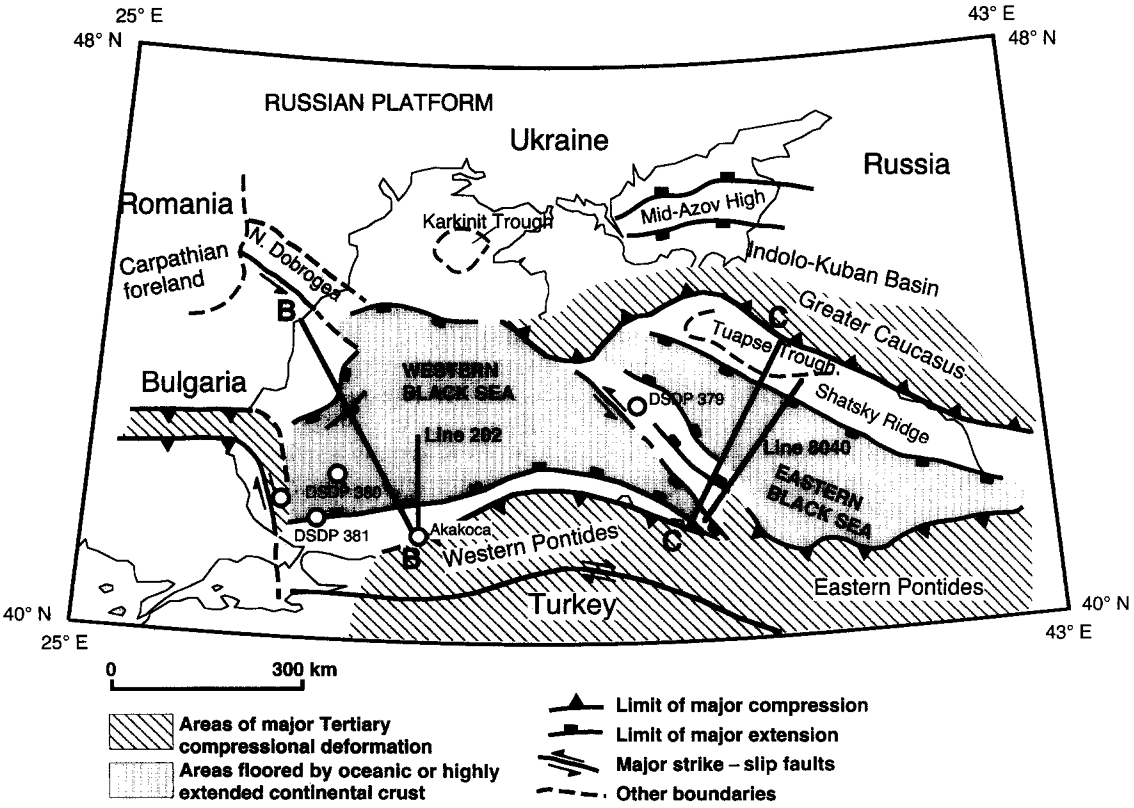


Figure 1 Location map showing major tectonic elements, the locations of the modelled profiles and of wells mentioned in the text and the locations of the seismic lines in *Figures 4* (Line 202) and *5* (Line 8040). Modified after Robinson *et al.* (in press b)

seismic data clearly show 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 volcaniclastic 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 Palaeocene is missing in the Eastern Pontides (Robinson *et al.*, 1995). 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.*, in press). In summary, in contrast with the situation in the Western Black Sea, where the stable Moesian Platform was rifted, rifting in the eastern basin apparently superimposed a younger extensional basin on an area that had already been a back-arc basin since the Early Jurassic.

With the exception of the Çağlayan and Ülüs formations exposed by Tertiary inversion in the Western and Central Pontides, there was apparently relatively little syn-rift sedimentation in either the West or, particularly, the East Black Sea. Albian sediments are known in the Romanian offshore, have been the targets for petroleum exploration and are the main reservoir in the Lebada Field (Robinson *et al.*, in press). Although we have not observed clear syn-rift geometries on seismic data the distribution of the Albian and its facies is notoriously difficult to predict in the area, a characteristic of syn-rift sediments. In Crimea, the Albian is mainly mudstone and shows rapid thickness changes, again supporting a syn-rift origin. In the Eastern Black Sea, the tilted fault blocks that dissect the rift margins — the Andrusov and Shatsky Ridges — show very few packages of divergent reflectors: syn-rift sediments appear to be almost absent.

Post-rift stratigraphy

Mapping and dating of post-rift sediments

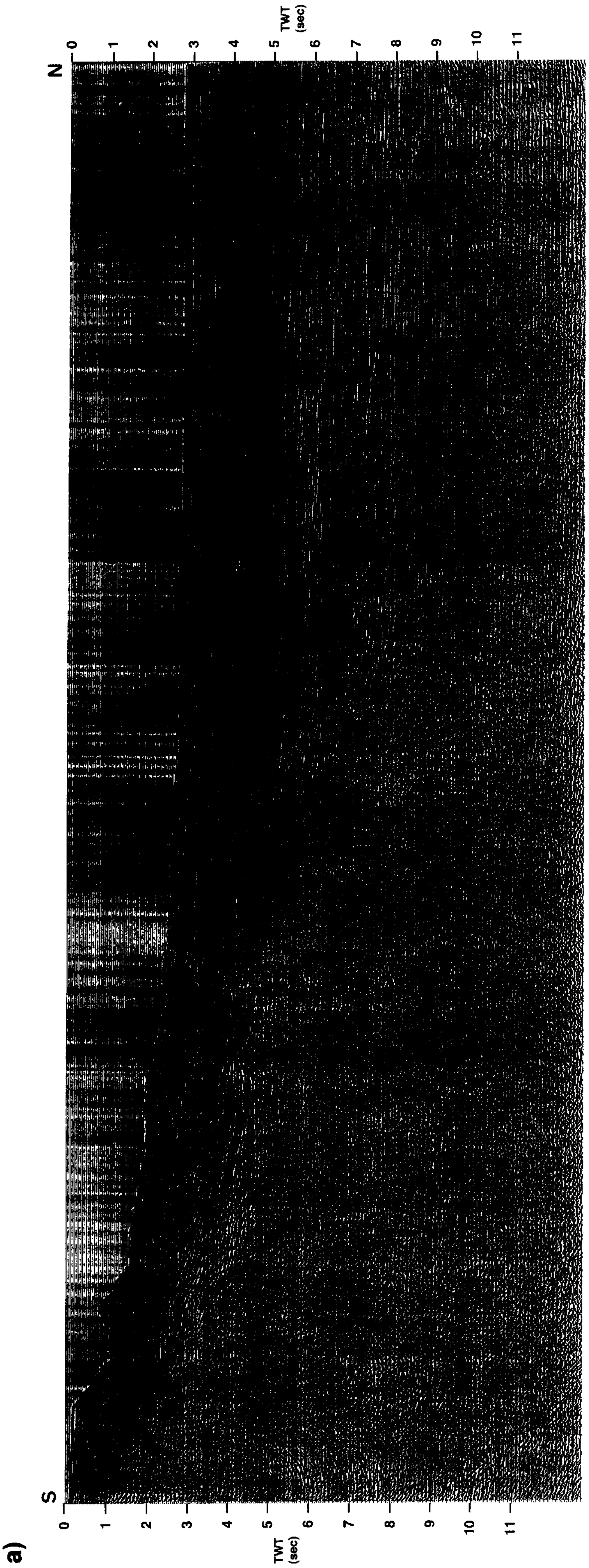
The total thicknesses of post-rift sediments in the Black Sea basins have been determined by picking acoustic basement on a regional reflection seismic grid and depth-converting using stacking velocities. The Western Black Sea post-rift fill is up to about 13 km thick in its centre (Upper Cretaceous to Recent); in the Eastern Black Sea, the post-rift fill is up to about 11 km thick (Middle Eocene to Recent). These figures differ slightly from estimates of Finetti *et al.* (1988), who ascribe a thickness of 13.5 km to the Western basin post-rift and 13 km to that in the Eastern Black Sea.

Dating seismic sequences within the Black Sea post-rift is rendered difficult by the poor well control. The large number of petroleum exploration wells on the Romanian shelf cannot be easily tied to the deep basin seismic data due to the complex gravity tectonics and growth faulting close to the present shelf edge. Similarly, exploration wells in the Gulf of Odessa cannot be tied into the basin because of the intervening high, the Kalamit Ridge. There are only three petroleum exploration and three DSDP wells that can be used to date the stratigraphy (*Figure 1*): Karadeniz-1 and Iğneada-1 located close to each other off the coast of Turkish Thrace, Akcakoca-1 off the coast of the Western Pontides, DSDP 380 and 381 north of the Bosporus and DSDP 379 located above the Mid-Black Sea High (Ross, 1978).

Karadeniz-1 and Iğneada-1 were drilled on compressional anticlines associated with the Tertiary Balkanide deformation. Iğneada-1 drilled a sequence that consisted of ?Quaternary and Pliocene sediments overlying a thick Miocene–Oligocene sequence and stopped in Upper Eocene sediments. Karadeniz-1 drilled a similar stratigraphy, but ended in Upper Cretaceous carbonates directly beneath thin Upper Eocene sediments. The stratigraphy in both of these wells can be tied with a reasonable degree of confidence to the reflection seismic data. Akcakoca-1 was drilled on a small ramp anticline related to Tertiary compression in the Pontides. It penetrated Quaternary–Pliocene sediments above a thick Eocene sequence, thin Palaeocene and Upper Cretaceous volcanics and tuffaceous carbonates. Akcakoca-1 stratigraphy can be tied accurately to Line BP91-202 (*Figures 2* and *2a*, and *Plate 1*) and the picks extended northwards into the Western Black Sea. All three petroleum exploration wells nonetheless lie close to the shore, in zones affected by Tertiary compression and submarine to subaerial erosion, both of which hinder extrapolation of stratigraphy away from the wells into the basin centre.

The DSDP wells lie within the post-rift basin, in areas unaffected by compression. Unfortunately, they do not penetrate stratigraphy older than Middle Miocene and have no sonic logs or check shots. DSDP wells 380 and 381 both penetrated the Miocene, whereas DSDP 379 stopped while still in the Quaternary at a depth of 624 m sub-seafloor (Schrader, 1978; Ross, 1978). Tying DSDP well stratigraphy to seismic data relies on the identification of unconformities and correlative conformities on seismic data and the identification of biostratigraphic breaks and condensed sections in the wells. This can be accomplished plausibly and our picks agree with those of Finetti *et al.* (1988).

Our ties from DSDP 380 and Akcakoca-1 indicate a thickness for the Quaternary of as much as 2.5 km in the centre of the Black Sea. This is greater than the maximum thickness determined by Finetti *et al.* (1988) because our seismic interpretation north and east from DSDP 380 suggests that the base Quaternary is deeper than these workers believed by about 800 m. In fact, Wong *et al.* (1994) have pointed out a thickness of more than 2000 m of the late Pleistocene to Recent deposits of the Danube fan complex in the middle of the Western Black Sea. Because our base Quaternary is lower, the Pliocene and Oligo-Miocene units are thinner in our interpretation than in that of Finetti *et al.* (1988). Our interpretation of the top Eocene and older markers is the same as that of Finetti *et al.* (1988).

a)
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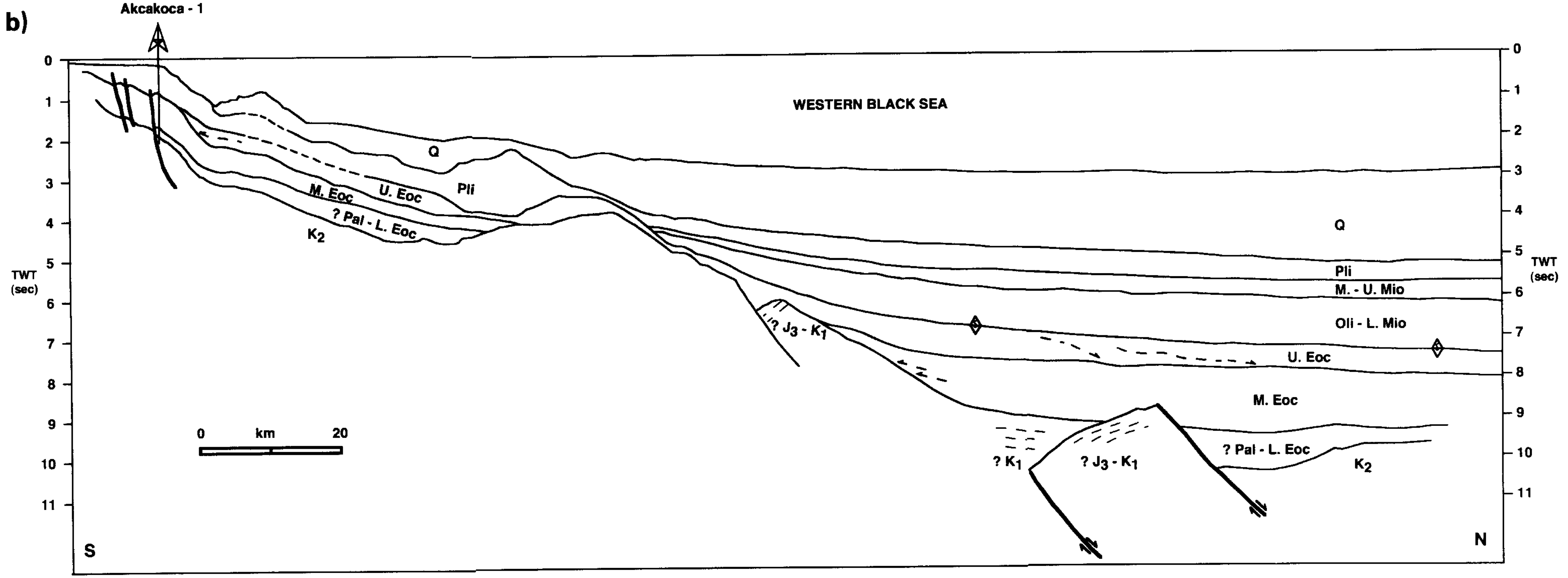

Figure 2 (a) Line BP91-202 and (b) interpretation. This line crosses the southern margin of the Western Black Sea and extends due north into the deep basin. The compressional deformation associated with the Western Pontides extends offshore only as far as Akcakoca-1. Beyond, to the north, all deformation is extensional. Note the difficulty of extending the Akcakoca stratigraphy into the deep basin

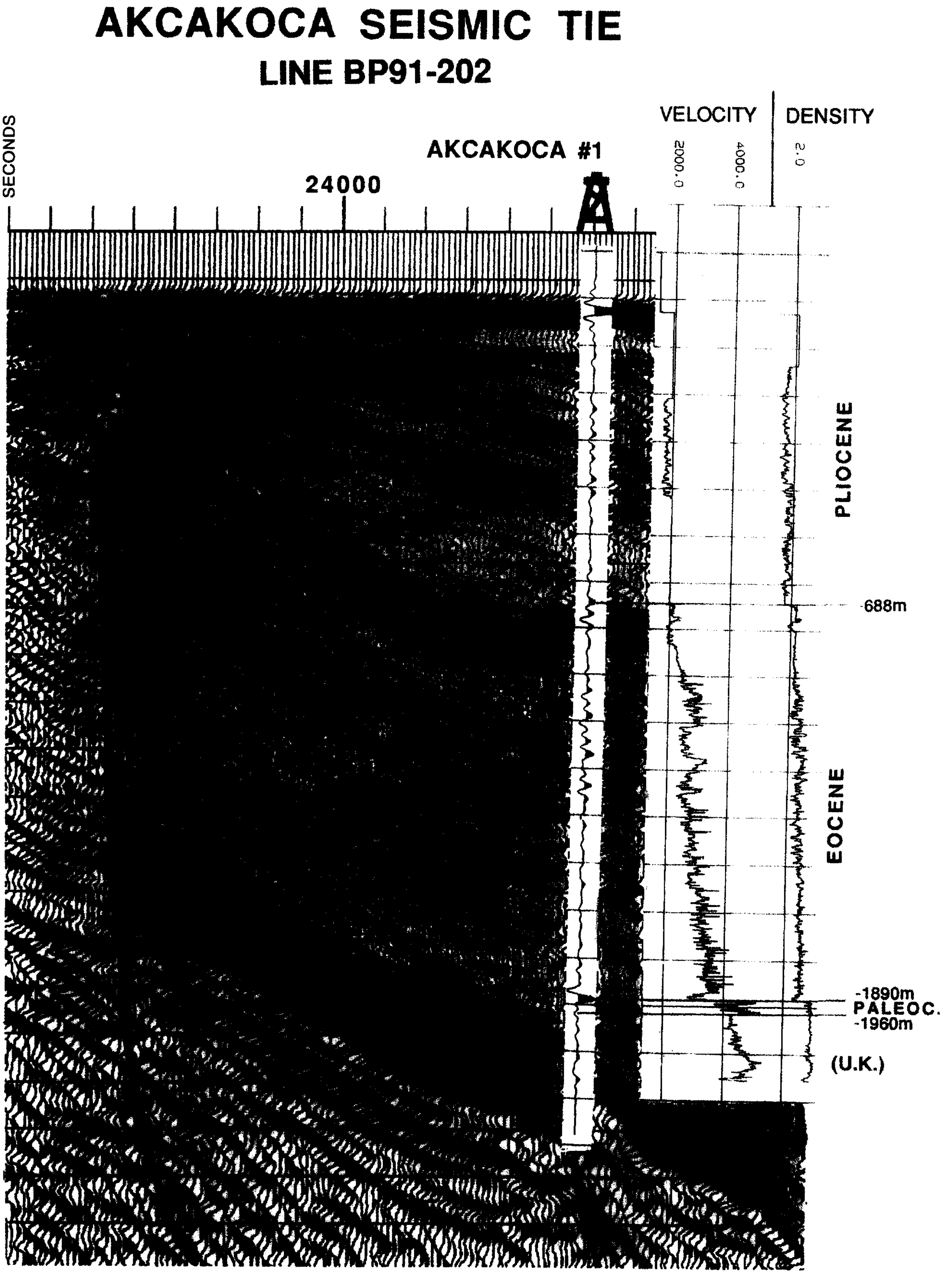

Plate 1 Akcakoca seismic tie. The synthetic seismogram for Akcakoca-1 is spliced into seismic line BP91-202. The match between the synthetic seismogram and the line is good and allows the well to be reliably transferred to the seismic line

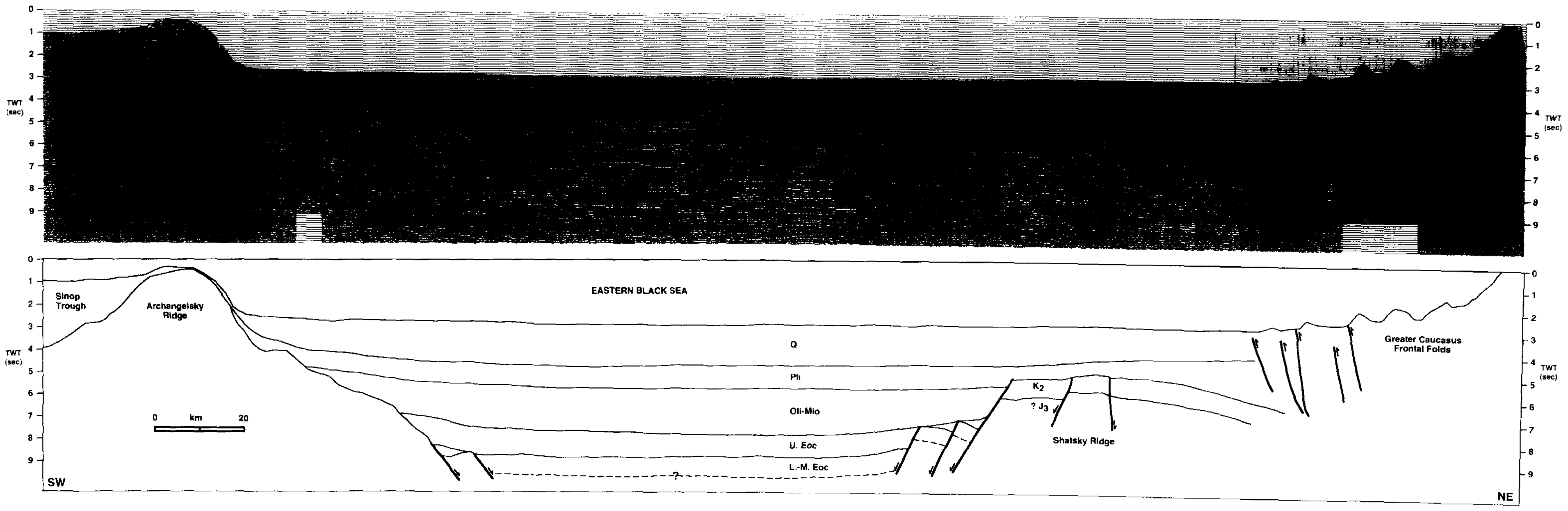

Figure 3 Line 8040 and interpretation. This line crosses the Eastern Black Sea, parallel to the direction of extension (SW–NE). The line shows compressional deformation affecting both edges of the basin: compressional structures are visible within at least the upper part of the Archangelsky Ridge and also at the thrust front of the Greater Caucasus. *The line also shows the clearly extensional geometry of the Shatsky Ridge* and confirms its status as the northern rift margin [the Shatsky Ridge has been interpreted by Finetti *et al.* (1988) as a compressional structure]. Note the absence of syn-rift erosion of the Shatsky Ridge, explicable by initiation of the rift on thin, hot lithosphere (no rift flank uplift) (Spadini *et al.*, in press)

Post-rift stratigraphy and facies

Figure 2 shows regional seismic lines and their stratigraphic interpretations across the Western and Eastern Black Sea, respectively. The top of the Upper Cretaceous can be tied into the Western Black Sea from Akcakoca-1 (though it is necessary to jump across several highs). The oldest post-rift sediments in the Western Black Sea are Cenomanian, so the base of the Upper Cretaceous is the top of acoustic basement in the central part of the basin. In the Central and Western Pontides, the Upper Cretaceous is a sequence of pelagic limestones (Kapanboğazı Formation), tuffs and minor lavas (Yemişliçay Formation), turbidites (Görsökü Formation) and tuffaceous chalks (Akveren Formation). North of the basin, in Romania and Crimea, the volcanic influence is diminished and the Upper Cretaceous to Danian is dominantly chalk. In the centre of the basin, as in most of the post-rift units, the Upper Cretaceous is characterized by parallel reflectors and probably comprises distal turbidites and chalks. In the Eastern Black Sea, the Upper Cretaceous is considered to form part of the pre-rift, forming the upper stratigraphic intervals in the tilted fault blocks of the Andrusov Ridge.

Upper Palaeocene to Eocene sediments exposed in the Western Pontides are mainly siliciclastic turbidites (Atbaşı and Kusuri formations). The lower part of the Kusuri Formation tends to include very coarse debris flows and slumps. Off the Turkish coast, Western Black Sea seismic data show mostly parallel reflectors, but there are numerous downlapping geometries in the Middle Eocene which onlap back towards the south. Given the occurrence of turbidites further south, these probably represent deep marine fans. In the Eastern Black Sea, the Late Palaeocene to Middle Eocene was the time of extension and basin formation. A drape unconformably overlying the tilted fault blocks of the Andrusov Ridge is probably a diachronous pelagic sediment as old as Lower Eocene. By the Middle and Late Eocene however, the Eastern Black Sea — like the Western basin — was being filled by siliciclastic turbidites. These include Upper Eocene oil-prone source rocks which have been exposed on the Russian coast by the Caucasus compression (Robinson *et al.*, in press). The Upper Eocene is particularly thick in the Eastern Black Sea (up to about 2 km); in the Western basin a separate Upper Eocene has not been mapped.

There is little direct evidence about the nature of Oligocene to Middle Miocene sediments in the Black Sea. Chronostratigraphic equivalents in Turkey are fluvial, evaporitic or volcanic, deposited in small basins related to compression in the Pontides. On the Crimean peninsula and in Romanian exploration wells, the interval is dominated by mudstones. Black Sea seismic data show the interval to be characterized by parallel reflectors and it seems likely that it comprises mainly turbidites.

The upper parts of the Miocene and younger sediments have been the subjects of intensive study in the DSDP wells. In DSDP 380, which lies close to the present abyssal plain, the Upper Miocene sediments include algal mats and peletal limestones indicative of very shallow water; the correlative interval in DSDP 381 which lies further up the shelf shows evidence of subaerial exposure (Stoffers *et al.*, 1978). A major pre-Pliocene unconformity can also be observed on seismic data from the Romanian shelf overlying Middle to Upper Miocene fluvial or shallow marine clastic sediments. During the Upper Miocene, the Black Sea thus appears to have been a fairly shallow lake. This near-desiccation of the basin has been related to a diversion of the regional drainage pattern by the growth of the Carpathians and their foreland basin and has been dated as Chersonian (equivalent to Early Sarmatian, earliest part of the Late Miocene; Kojumdgieva, 1983). As such it is not directly related to the later Messinian desiccation of the Eastern Mediterranean. The stratigraphy of the DSDP wells shows that base level rose rapidly through the Pliocene and Quaternary; the sea is about 2200 m deep in the basin centre today. During the Quaternary, the Black Sea was often isolated from the Mediterranean because of the sill height of the Bosporus, becoming a deep lake.

Stratigraphic modelling: methods, assumptions and approach

To investigate the subsidence history of the Black Sea area using a stratigraphic modelling approach, we need to isolate the tectonic component of the vertical movements. We need to define the parameters controlling the lithospheric thinning and, thus, the tectonic subsidence pattern during the evolution of the basin. Once we have determined the tectonic component, we can predict the water depth evolution, sea-level change and total basement subsidence that can best simulate the depositional history of the Western and of the Eastern Black Sea Basins.

Lithospheric and crustal thinning of the Black Sea area have been modelled by Spadini *et al.* (in press), who show that the opening of the Black Sea basins and the crustal thinning of the area can be simulated by pure shear deformation, taking into account a finite duration of rifting and non-zero lithospheric strength during the rifting and post-rift periods (Kooi *et al.*, 1992). The main results of the modelling are that the Western and Eastern Black Sea were initiated on lithosphere with very different thicknesses, geothermal gradients and associated mechanical properties. The Western Black Sea formed by rifting of thick (≈ 200 km) and therefore cold lithosphere with high mechanical strength and an associated deep depth of necking (≈ 25 km). This thick lithosphere was in fact the stable continental Moesian Platform. In contrast, the Eastern Black Sea developed by rifting of thin (≈ 80 km) and therefore hot and weak lithosphere, with a shallower depth of necking (15 km). This is compatible with the development of the Eastern Black Sea on the site of an earlier (Mesozoic) back-arc basin. The differences in initial lithospheric conditions (see also Cloetingh *et al.*, this issue) between east and west explain differences in total subsidence and the absence of rift flank uplift in the east.

In this paper we use the model derived by Spadini *et al.* (in press) to simulate the post-rift stratigraphy established by mapping and interpreting reflection seismic. The parameters adopted to reproduce the observed crustal deformation of the Western Black Sea

Table 1 Model parameters

	Value	Definition
a^1	200 km	Initial lithospheric thickness WBS
a^2	80 km	Initial lithospheric thickness EBS
c	35 km	Initial crustal thickness
Z^1	25 km	Depth of necking WBS
Z^2	15 km	Depth of necking EBS
T_e	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

WBS = Western Black Sea; EBS = Eastern Black Sea; EET = effective elastic thickness

and of the Eastern Black Sea are given in *Table 1*: they represent a set of values that is consistent with the observed crustal geometries and gravity anomalies. For a sensitivity analysis of these parameters we refer to Spadini *et al.* (in press). This set of parameters constitutes our starting point in investigating the subsidence pattern (tectonic component plus the sediment/water loading) during rift and post-rift times. With the tectonic component of basin subsidence established, the only variables controlling sediment and water loading and thus stratigraphy are: (1) sediment and water densities; (2) variation of sea level; (3) palaeo-water depth. In our approach, subsidence is calculated using a two-dimensional pure shear McKenzie (1978) type model, modified to include a finite duration of stretching and lateral heat flow during rift and post-rift times. For each step during basin evolution the tectonic component of subsidence is calculated considering the adopted thinning factors (Spadini *et al.*, in press) and

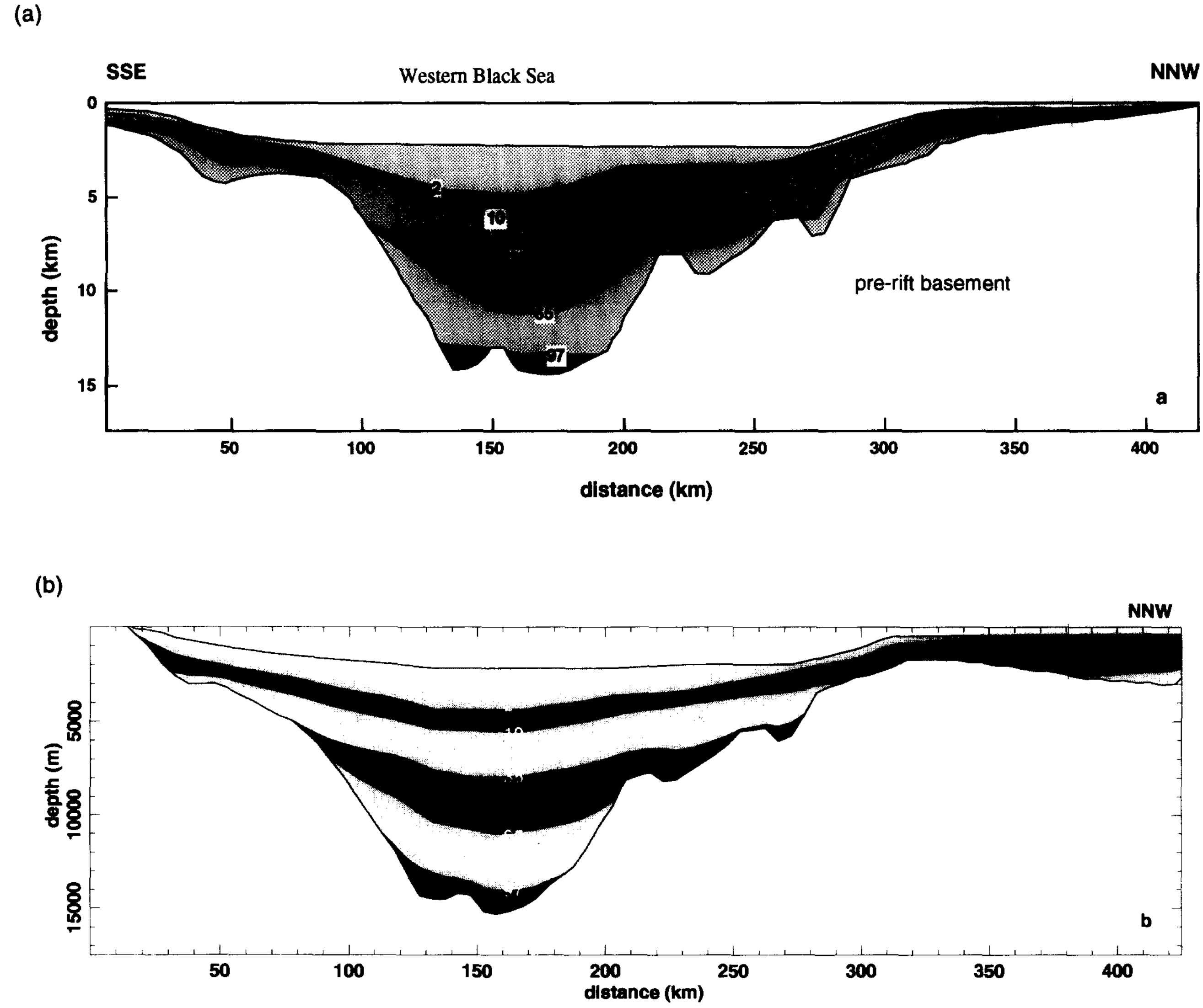

Figure 4 (a) Observed and (b) predicted stratigraphy. Western Black Sea (Akcakoca Profile) (line B–B in *Figure 1*). Markers represent end-Albian (97 Ma, end of rifting), end-Cretaceous (65 Ma), end-Eocene (35 Ma), intra-Sarmatian (10 Ma, the age of major sea-level fall) and end-Pliocene (2 Ma)

the induced thermal perturbation. The space between the calculated basement position and sea level is then filled by sediments up to a specified palaeo-water depth profile along the analysed transect (sediment–water interface). Taking into account sediment compaction, using an exponential porosity–epth relation (*Table 1*), the tectonic subsidence is corrected to obtain the total basin subsidence (basement subsidence). With a trial and error procedure, we then let the position of the sediment–water interface vary to obtain the observed thickness for each sedimentary unit deposited during the evolution of the basin (*Figures 4* and *5*). Predictions of the time-dependent water depth values and the corresponding basement subsidence are the goal of our modelling procedure.

When modelling of basement subsidence is carried out including mechanical compaction of sedimentary units, it is commonly assumed that the thickness and total mass of the unit will decrease as pore fluid is progressively expelled (Sclater and Christie, 1980). For the purpose of numerical modelling it is convenient to define a simple porosity–depth function as

$$\phi(z) = \phi_0 \exp(-cz)$$

where z is the depth of the considered unit, ϕ_0 denotes surface porosity and c is the characteristic depth constant (see Table 1 for adopted values). Errors in defining ϕ_0 and c lead to errors in basement subsidence predictions and, thus, in the estimate of palaeo-water depth values required to fit the observed stratigraphy. An error analysis by Gallagher (1989) pointed out that fluctuations of ± 100 m of subsidence curves are possibly within the error range of the adopted porosity–depth relation and, thus, they cannot be correctly interpreted without additional constraints. In fact, in the following, we will not address the problem of identifying and interpreting the small amplitude variations of subsidence trends and of related palaeo-water depths, especially for deeply buried units, for which the error is statistically higher. We will describe and discuss the general trend that defines the evolution of the Western and of the Eastern Black Sea Basin. As a matter of fact, this general trend is relatively insensitive to variations in the porosity–depth function (Watts and Steckler, 1981).

During our modelling procedure we have assumed that eustatic sea-level variations have been small relative to the huge water depth changes to which the Black Sea basins have apparently been subjected. Maximum changes of the order of 200 m have been suggested by Haq *et al.* (1987) and the model is not particularly sensitive to these, particularly in the centre of the basin. During the Sarmatian, however (10 Ma), a major sea-level fall is inferred by the stratigraphy of the DSDP wells and by major erosive unconformities around the basin margins. This large sea-level change

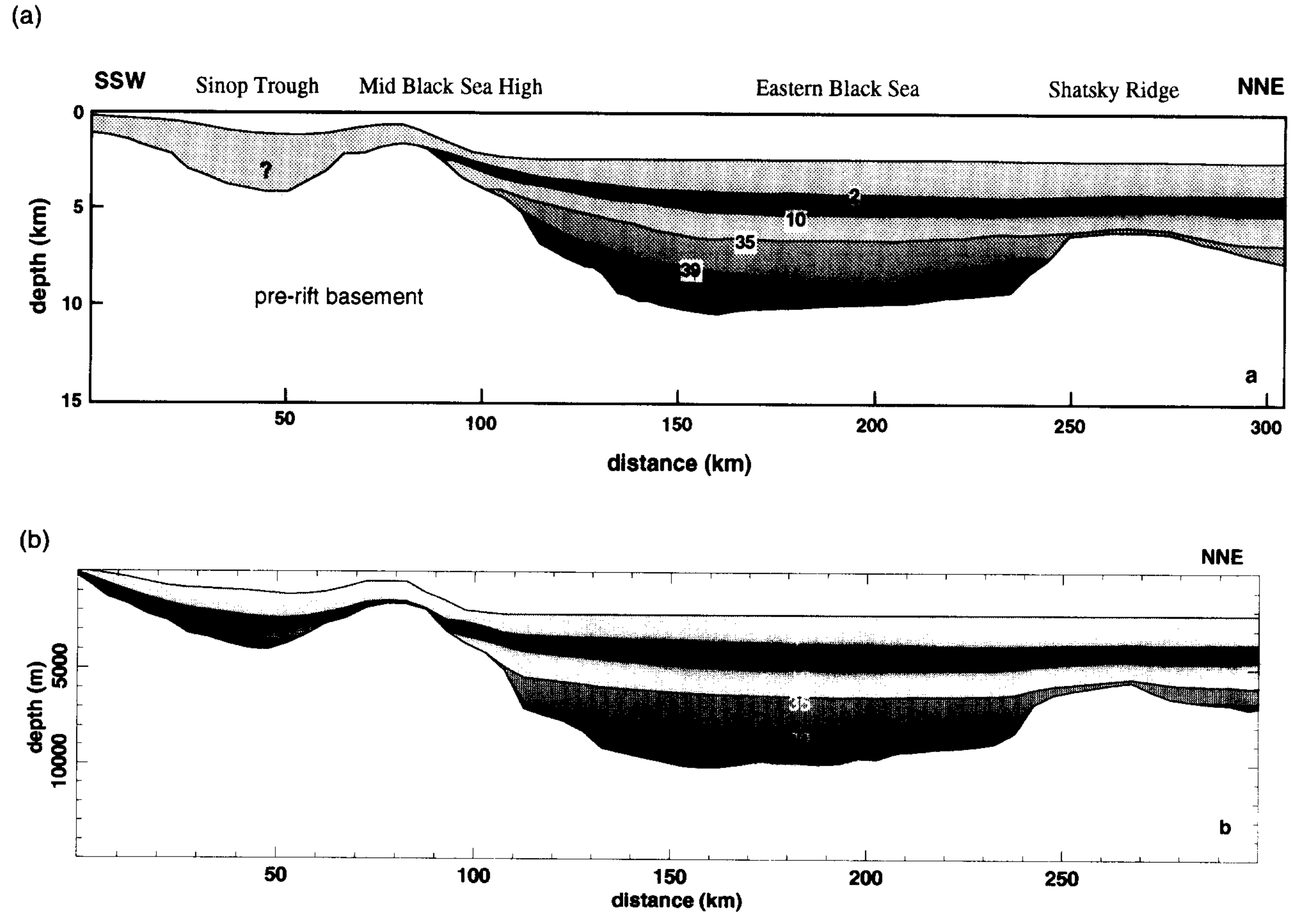

Figure 5 (a) Observed and (b) predicted stratigraphy, Eastern Black Sea (Badut Profile) (line C–C in *Figure 1*). Markers represent end-Early Eocene (52 Ma, end of rifting), end-Middle Eocene (39 Ma), end-Eocene (35 Ma), intra-Sarmatian (10 Ma, the age of major sea level fall) and end-Pliocene (2 Ma)

has to be incorporated in our model: we now have two variables to fix to simulate the stratigraphy at the beginning of the Sarmatian (10 Ma). The water depth during the Late Miocene at the basin margin has been estimated as between 0 and 100 m from biostratigraphic and palaeoenvironmental studies from DSDP 380 and 381 (Ross, 1978; Schrader, 1978). According to our modelling calculations, to explain both the observed thickness of the pre-(?)Sarmatian Oligocene to Miocene sediments and the suggested water depth of 100 m at the edge of the present bathyal plain, a sea-level fall of 1500 m is required. The value, which represents an outcome of our modelling procedure, can be applied to all the area and this allows us to constrain from stratigraphic modelling the water depth profile for the considered sections at 10 Ma.

Results

Figures 4 and *5* show modelled and observed stratigraphies along one profile in the Western Black Sea (Akcakoca) and one in the Eastern Black Sea (Badut). Taking into account the fact that the palaeo-water depth was the only free parameter during the modelling procedure, the modelled stratigraphies have to be considered as the best fit. The match of model to observed stratigraphies is always good in the basin centres; on the margins there are some mis-matches. The northern part of the modelled stratigraphy on the Akcakoca section shows a sediment package thickening northwards towards the Russian Platform, whereas, in reality, the Black Sea strata thin and onlap northwards. The reason is probably due to the profile running parallel to a bend in the Moho depth contours of Belousov *et al.* (1988); the Moho is thus flat along the northern part of the profile even though the regional pattern is that the Moho falls northwards. We thus believe this mis-match to be an artefact of the contouring of the Moho depth. The SSE end of the Akcakoca profile (*Figure 4*) is located at the boundary with the contractional structures of the Western Pontides (*Figure 1*). Differences between the observed and predicted stratigraphy are related to compressional deformation of the margin that has not been taken into account on our model. The modelled Badut profile in the Eastern Black Sea (*Figure 5*) shows an excellent fit with the observed stratigraphy. We have no information on the geometry of the sequence boundaries in the Sinop Trough, the SSW end of the profile. For that area we predict a stratigraphy characterized by syn-rift deposition (end of rifting at 52 Ma) and by the presence of an erosional

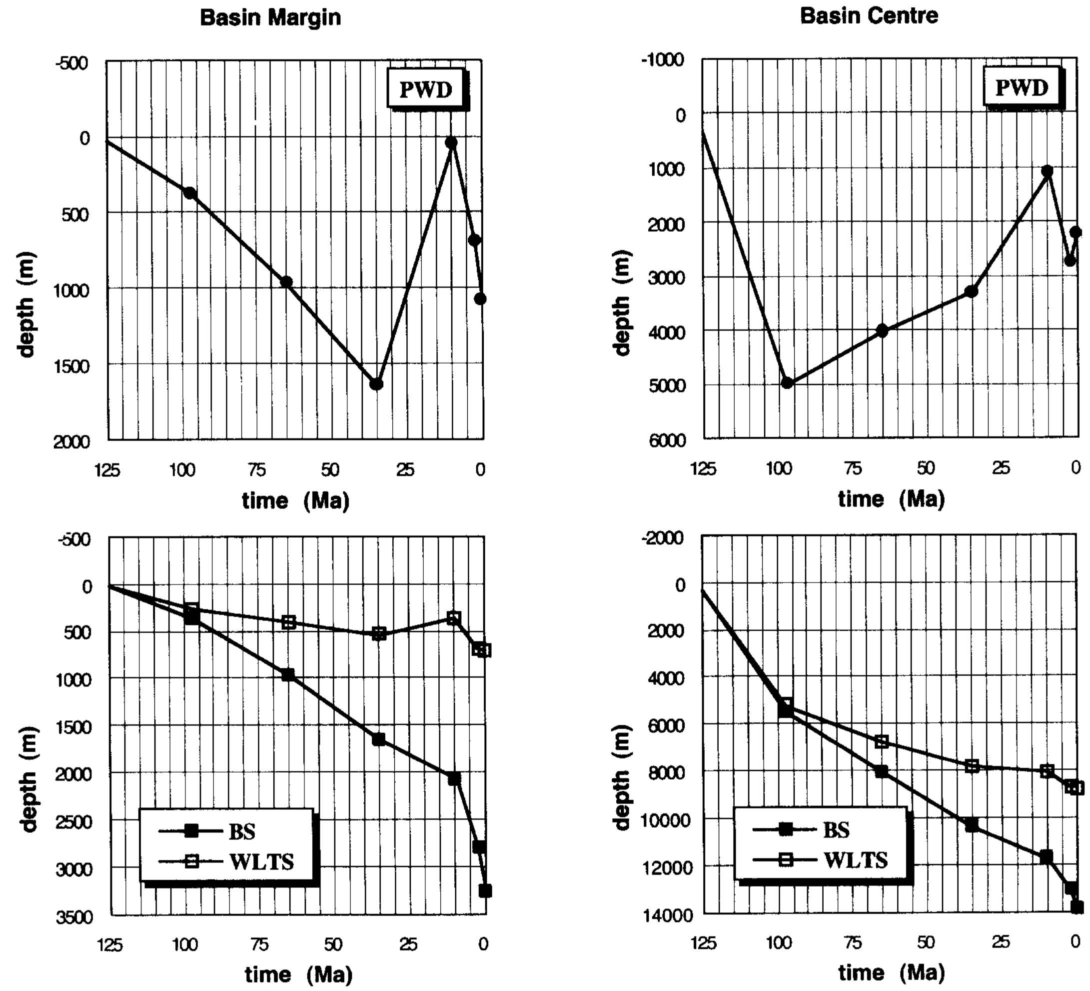

Figure 6 Representative subsidence curves for the Western Black Sea. The curves show the calculated palaeo-water depth histories (upper panels) and basement subsidence (BS) and water-loaded tectonic subsidence (WLTS) for a point near the basin margin and another in the basin centre. Note the difference in vertical scale between the basin margin and the basin centre

unconformity in the Early Sarmatian (10 Ma) as a consequence of the sea-level fall.

The model reproduces several notable features of the stratigraphy of the Black Sea: the apparent near-absence of syn-rift strata (other than in the Western Pontides); a thick Upper Eocene; a relatively thin Oligocene to Miocene and a very thick Quaternary.

The modelled stratigraphies of *Figures 4* and *5* have been fitted to the observations by varying palaeo-water depth histories. These are calculated assuming no sea-level variation until the 1500 m fall during the Sarmatian with a subsequent return to present day sea level. *Figures 6* and *7* show the basement subsidence, the water-loaded tectonic subsidence and the palaeo-water depth profiles that provide the best fits of modelled to observed stratigraphy for points on the margins and in the centres of the Western and Eastern Black Sea basins. The figures show a number of significant features predicted by the modelling.

1. There is rapid basement subsidence during rifting to abyssal depths in the centres of both basins. At the end of rifting, the Western Black Sea was around 5000 m deep and the Eastern Black Sea 4000 m deep. Such rapid subsidence and great water depths would have favoured starvation of the basin. This deduction is therefore consistent with the rather limited development of syn-rift sediments in both basins other than close to the southern margin of the Western Black Sea in the Western Pontides.
2. After rifting was completed, the water depth generally decreased in the depocentres but increased at the basin margins (*Figures 6* and *7*). This suggests that most sediment was by-passing the basin margins, leading to high sedimentation rates in the basin centres which were able to compensate for the post-rift thermal subsidence. The most dramatic example of this effect is observed in the thick Upper Eocene sediments of the Eastern Black Sea. This must reflect an increase in sediment supply sufficient to compensate for the thermal subsidence and to begin to fill up the basin towards sea level. This comes out from the analysis of predicted subsidence curves for the Eastern Black Sea (*Figure 7*). The basement subsidence shows a sharp acceleration between 39 and 35 Ma. On the contrary, the predicted tectonic subsidence does not accelerate, indicating that the feature is related to sediment loading (i.e. increased sedimentation rate). A decrease in water depth from 3600 to 2800 m is implied during the Late Eocene. Late Eocene is in fact the age of onset of compressional deformation in

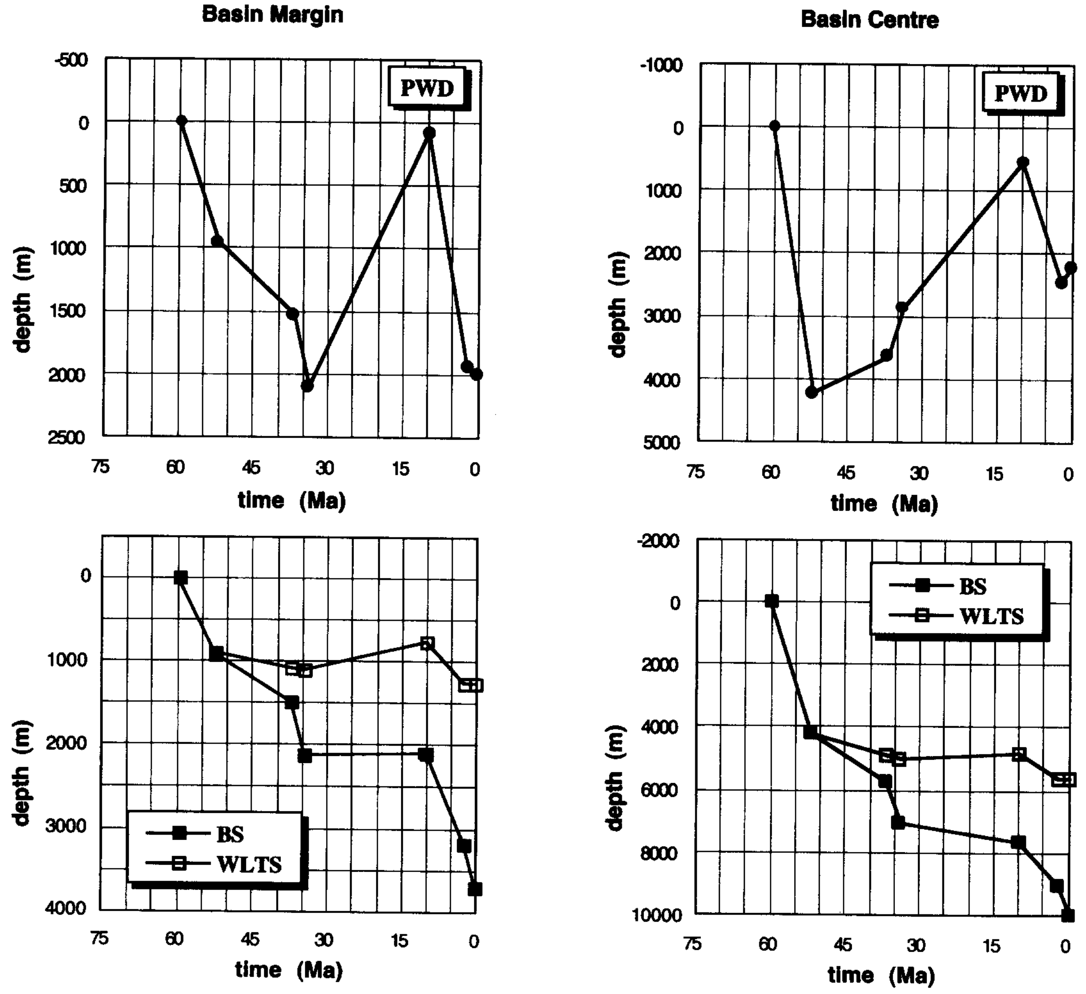

Figure 7 Representative subsidence curves for the Eastern Black Sea. The curves show the calculated palaeo-water depth histories (upper panels) and basement subsidence (BS) and water-loaded tectonic subsidence (WLTS) for a point near the basin margin and another in the basin centre. Note the difference in vertical scale between the basin margin and the basin centre

the Greater Caucasus; in the Pontides it was a time of major compression, and, in the east, volcanic arc development.

3. During the Late Miocene, replacing the 1500 m of water that was removed at the beginning of the Sarmatian has the effect of increasing the water-loaded tectonic subsidence and thus basement subsidence (*Figures 6* and *7*). As a result, the water depth increases dramatically during the Late Miocene and Pliocene to around 2.8 km in the west and to 2.4 km in the east at the beginning of the Quaternary.
4. By the Quaternary, the effect of the replaced water on tectonic subsidence had ceased. Nonetheless, continued basement subsidence is required to accommodate the large thickness of Quaternary

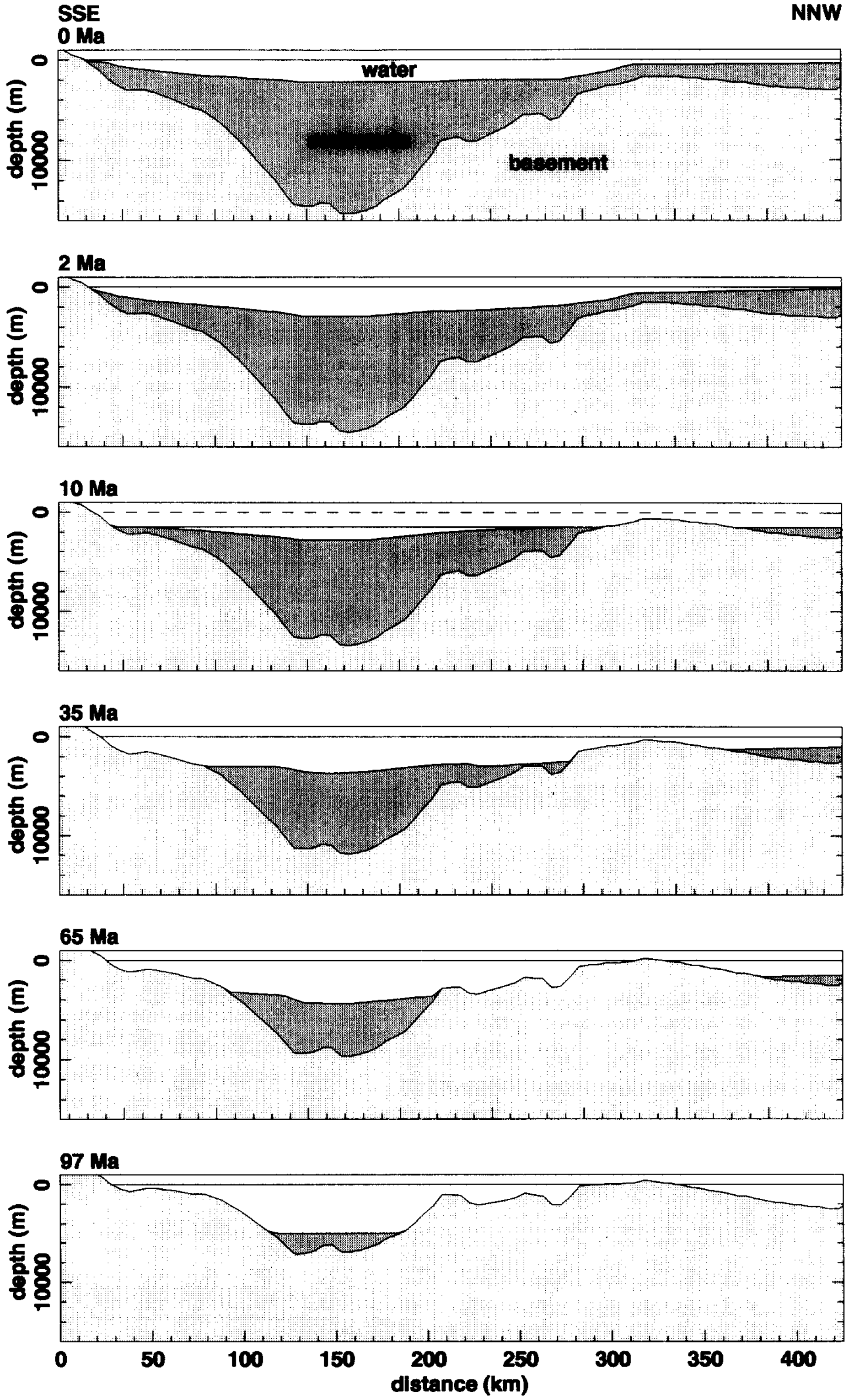

Figure 8 Evolution of the Western Black Sea (Akcakoca profile). The backstripped section (line B–B in *Figure 1*) shows the pre-rift basement, sediment thickness, water depth and the position of sea level for each phase (corresponding to the sequence boundaries of *Figure 5*) in the evolution of the basin

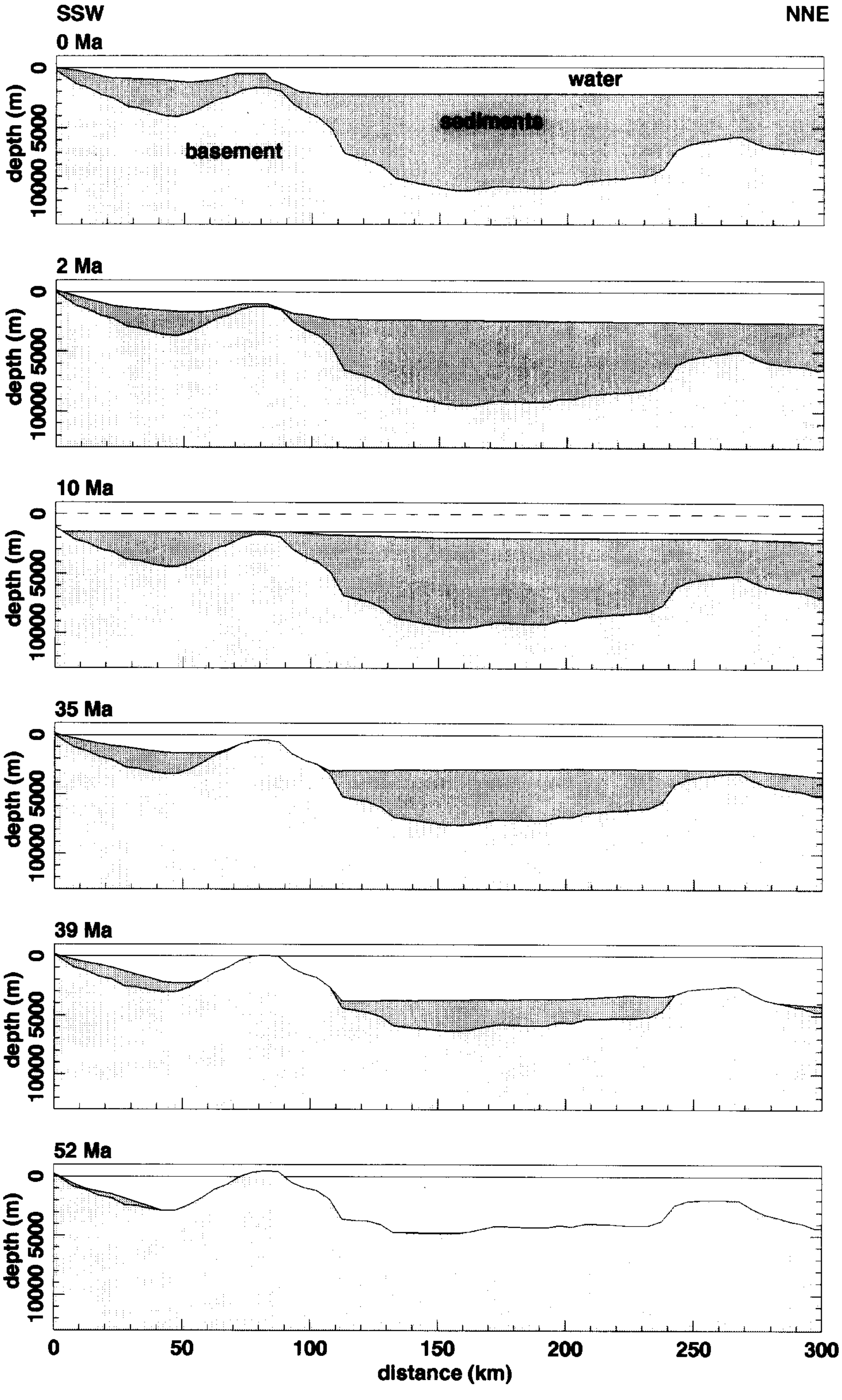

Figure 9 Evolution of the Eastern Black Sea (Badut profile). The backstripped section (line C–C in *Figure 1*) shows the pre-rift basement, sediment thickness, water depth and the position of sea level for each phase (corresponding to the sequence boundaries of *Figure 6*) in the evolution of the basin

sediments. This must be due to an increase in sediment supply and associated loading. Again, a comparison between basement subsidence and water-loaded tectonic subsidence between 2 and 0 Ma highlights the key role of the increasing sedimentation rate in controlling the subsidence rate. The extra sediment may have come into the Black Sea due to glaciation of much of the catchment area in northern Europe. An important part could have also been played by the Danube river, which started to contribute to the Black Sea Basin fill with a large amount of sediments, starting from the late Pleistocene (Wong *et al.*, 1994). The load required actually implies a minor decrease in water depth in the basin centre from the end of the Pliocene to today's 2200 m.

Conclusions

Figures 8 and *9* summarize the development of the Western and Eastern Black Sea, predicted by the modelling, from the end of rifting to the present day. The Western Black Sea began rifting in the Late Barremian and, by the Cenomanian, was a deep (≈5000 m) marine basin with oceanic crust and limited syn-rift sediments towards the basin centre. Though the water depth decreased through the Late Cretaceous, Palaeocene and early Neogene, the deep basin persisted until the Sarmatian sea-level fall, which reduced the basin to a relatively small lake up to around 800 m deep in the centre. The Eastern Black Sea began rifting in the Late Palaeocene and subsided rapidly with little rift flank uplift or erosion to form a deep (≈4000 m) marine basin. A draping horizon is visible on seismic data over parts of the rift margins (e.g. Andrusov Ridge) and may be interpreted as pelagic. During the Late Eocene, an increase in sediment supply from compressional belts to the Pontides or possible Greater Caucasus led to the deposition of a thick Upper Eocene sequence (including oil-prone source rocks) and a consequent decrease in water depth from 3600 to 2800 m. Like its western counterpart, the Eastern Black Sea remained a deep basin until the Sarmatian so that all Upper Eocene to Middle Miocene sediments will be of deep water origin. The Eastern Black Sea was also converted into a lake during the Sarmatian, up to about 400 m deep on the Badut profile. As the sea level returned to normal in the Late Miocene, the water depth increased dramatically to 2800 m in both Eastern and Western basins due to the loading effect of the water. During the Quaternary, increased sediment supply led to significant subsidence and sediment accumulation, but the water depth decreased only slightly to the present day value of 2200 m.

Acknowledgements

Financial support for this work was provided by the IBS (Integrated Basin Study) project, funded by the Commission of the European Communities (Contract No. JOU2-CT 92-0110) and by the Peri-Tethys project. W. Fjeldskaar and C. Dinu provided useful comments on the manuscript. Publication 950319 of the Netherlands Research School of Sedimentary Geology.

References

Belousov, V. V., Volvovsky, B. S., Arkhipov, I. V., Buryanova, B. V., Evsyukov, Y. D., Goncharov, V. P., Gordienko, V. V., Ismagilov, D. F., Kislov, G. K., Kogan, L. I., Kondyurin, A. V., Kozlov, V. N., Lebedev, L. I., Lokholatnikov, V. M., Malovitsky, Y. P., Moskalenko, V. N., Neprochnov, Y. P., Otisty, B. K., Rusakov, O. M., Shimkus, K. M., Shlezinger, A. E., Sochelnikov, V. V., Sollogub, V. B., Solovyev, V. D., Starostenko, V. I., Starovoitov, A. F., Terekhov, A. A., Volvovsky, I. S., Zhigunov, A. S. and Zolotarev, V. G. (1988) Structure and evolution of the earth's crust and upper mantle of the Black Sea *Boll. Geofis. Teor. Appl.* **30**, 109–196

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

Gallagher, K. (1989) An examination of some uncertainties associated with estimates of sedimentation rates and tectonic subsidence *Basin Res.* **2**, 97–114

Golmshtok, A. Y., Zonenshein, L. P., Terekhov, A. A. and Shainurov, R. V. (1992) Age, thermal evolution and history of the Black Sea Basin based on heat flow and multichannel reflection data *Tectonophysics* **210**, 273–293

Görür, N. (1988) Timing of opening of the Black Sea basin *Tectonophysics* **147**, 247–262

Haq, B. U., Hardenbol, J. and Vail, P. R. (1987) Chronology of fluctuating sea levels since the Triassic *Science* **235**, 1156–1167

Kojumdgieva, E. (1983) Palaeogeographic environment during the dessication of the Black Sea *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **43**, 195–204

Kooi, H., Cloetingh, S. and Burrus, J. (1992) Lithospheric necking and regional isostasy at extensional basins. 1. Subsidence and gravity modelling with an application to the Gulf of Lion Margin (SE France) *J. Geophys. Res.* **97**, 17 553–17 571

Letouzey, J., Bijou-Duval, B., Dorkel, A., Gonnard, R., Kristchev, K., Montadert, L. and Sungurlu, O. (1977) The Black Sea: a marginal basin; geophysical and geological data. In: *International Symposium on the Structural History of the Mediterranean Basins* (Eds B. Bijou-Duval and L. Montadert), Editions Technip, Paris, 363–376

Manetti, P., Boccaletti, M. and Peccerillo, A. (1988) The Black Sea: remnant of a marginal basin behind the Srednegorie–Pontides island arc system during the Upper Cretaceous–Eocene times *Boll. Geofis. Teor. Appl.* **30**, 39–51

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

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

Robinson, A. G., Banks, C. J. Hirst, J. P. P. and Rutherford, M. M. (1995) Stratigraphic and structural development of the Eastern Pontides, Turkey *J. Geol. Soc. Lond.* **152**, 861–872

Robinson, A. G., Banks, C. J. and Rudat, J. H. Petroleum geology of the Black Sea *Mar. Petrol. Geol.*, in press

Ross, D. A. (1978) Summary of results of Black Sea drilling *Init. Rep. DSDP* **XLII**, 1149–1177

Rudat, J. H. and Macgregor, D. S. (1993) Unconventional exploration techniques in a high cost deep water basin: a case study from the Black Sea *Soc. Expl. Geophys. Abstr. Progr.*

Schrader, H. J. (1978) Quaternary through Neogene history of the Black Sea deduced from the palaeocology of diatoms, silicoflagellates, ebridians and chrysomonads *Init. Rep. DSDP* **XLII**, 789–902

Sclater, J. G. and Christie, P. A. F. (1980) Continental stretching: an explanation of post mid-Cretaceous subsidence of the central North Sea *J. Geophys. Res.* **85**, 3711–3739

Spadini, G., Robinson, A. G. and Cloetingh, S. A. P. L., Western versus Eastern Black Sea tectonic evolution: pre-rift lithospheric controls on basin formation *Tectonics*, in press

Stoffers, P., Degens, E. T. and Trimonis, E. A. (1978) Stratigraphy and suggested ages of Black Sea sediments *Init. Rep. DSDP* **XLII**, 483–487

Watts, A. B. and Steckler, M. S. (1981) Subsidence and tectonics of Atlantic-type continental margins *Oceanol. Acta* **4** (suppl. no. SP), 143–153

Wong, H. K., Panin, N., Dinu, C., Georgescu, P. and Rahn, C. (1994) Morphology and post-Chaudian (Late Pleistocene) evolution of the submarine Danube fan complex *Terra Nova* **6**, 502–511

Zonenshain, L. P. and LePichon, X. (1986) Deep basins of the Black Sea and Caspian Sea as remnants of Mesozoic back-arc basins *Tectonophysics* **123**, 181–212