A kinematic modelling approach to lithosphere deformation and basin formation: application to the Black Sea

S. S. EGAN[1] & D. J. MEREDITH[2]

[1]*Earth Sciences and Geography, School of Physical and Geographical Sciences, Keele University, Keele, Staffordshire ST5 5BG, UK (e-mail: s.s.egan@esci.keele.ac.uk)*

[2]*Grid Technology Group, Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK (e-mail: d.j.meredith@dl.ac.uk)*

Abstract: A kinematic model of lithosphere deformation has been developed that integrates the following components: structural deformation of the crust and mantle lithosphere; thermal conditioning, perturbation and subsequent re-equilibration of the lithosphere temperature field; flexural isostatic adjustments; and surface processes, including both lateral and temporal variations in basin fill and bathymetry. This approach enables the forward modelling of extensional basin evolution in two and three dimensions followed by deformation due to subsequent extensional and compressional (i.e. inversion) events.

The model has been applied to the Black Sea, which is one of the deepest basins in the world and yet it is poorly understood in terms of the mechanisms that have controlled its evolution. Although it is widely accepted that this basin was initiated by Mesozoic back-arc extension related to the subduction of the Tethys Plate to the south, most of the subsidence observed today occurred within the Palaeogene and Neogene (i.e. within the framework of the Alpine–Himalayan orogenic belt). The modelling approach described above has been used to test possible geological and geodynamic mechanisms that have controlled the subsidence history of the Black Sea. In particular, the investigation has focused on trying to explain the anomalously thick post-rift subsidence that occurred in the basin. Models assuming uniform lithosphere extension do not generate the observed thickness of sediment infill in the basin. Similarly, modelling of the compressional deformation around the edges of the basin structure does little to explain the large magnitude of subsidence within the centre of the basin. Model results show that the observed basin depths can be attained only when the total magnitude of deformation is constrained from crustal thickness changes rather than by fault displacement measurements.

Kinematic models define the dimensions of all components of a system as well as a set of relationships that describe how the parts in the system interact and evolve. This paper is concerned with the kinematic modelling of the geological and geodynamic processes that occur during the extension and compression of the continental lithosphere, but placing emphasis on how this deformation controls uplift and subsidence at the surface. The main advantage of the kinematic modelling of lithosphere-scale deformation is that it can be used to investigate the effects of processes that are poorly constrained by geophysical and field data, and to provide a better understanding of the structural, thermal and stratigraphic development of deep frontier basins where well control is poor.

The first kinematic models of lithosphere extension and basin formation (e.g. McKenzie 1978; Royden & Keen 1980) combined the crustal thinning, thermal and local isostatic processes associated with the instantaneous stretching of the lithosphere to quantify surface subsidence or, sometimes, uplift. Although these models are now considered relatively simplistic, they are based on concepts that underpin much of the lithosphere-scale basin modelling being carried out today. One of the main aims of this paper is to describe the individual processes that play a key role in deformation at lithosphere scale and how these processes have been integrated within a two-dimensional (2D) and 3D kinematic modelling environment. This approach enables the forward modelling of extensional basin evolution followed by subsequent extensional or compressional deformation.

The modelling approach has been applied to provide insights into the evolution of a specific case study in the geological record, namely the Black Sea. The evolution of the Black Sea region represents an interference of tectonic events over geological time in that most of the subsidence (up to 14 km) took place within the basin when the immediate surrounding regions were experiencing compressional deformation. Few modelling studies have focused on the evolution of the Black Sea such that the mechanisms that have controlled

From: Karner, G. D., Manatschal, G. & Pinheiro, L. M. (eds) *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*. Geological Society, London, Special Publications, **282**, 173–198.
DOI: 10.1144/SP282.9 0305-8719/07/$15.00

the subsidence history of the basin remains poorly constrained (Brunet & Cloetingh 2003). The main aim of this case study is to both test and apply 2D and 3D kinematic models of lithosphere extension to obtain a better understanding of the geological and geodynamic processes that have contributed to the subsidence history of the Black Sea basin. Models have been generated to investigate the evolution of the basin in the context of uniform lithosphere extension, compressional deformation and loading at the edges of the basin, and depth-dependent lithosphere extension in the lower crust and mantle lithosphere.

The modelling has also been applied to the Iberian margin as part of a benchmarking exercise for the comparison of different modelling approaches carried out as part of the 2004 InterMARGINS Extensional Deformation of the Lithosphere (IMEDL) workshop (see the Appendix).

Lithosphere extension and basin formation: historical background

The deformational response of a rheologically layered lithosphere to applied tensional and compressional forces is highly variable. A wide range of basin-scale phenomena have been attributed to the varying mechanisms of lithosphere-scale deformation, such as the difference in width between extending regions (e.g. Buck 1991) and the generation of asymmetric rift basins (Coward 1986). Despite the complexity of lithosphere-scale deformation, crustal thickness changes are generally modelled by either simple shear (i.e. faulting and 'brittle' deformation: e.g. Wernicke 1985) or pure shear (i.e. stretching or squashing: e.g. McKenzie 1978) or by a combination of the two (e.g. Kusznir *et al.* 1987). The pure shear and simple shear mechanisms represent end-member lithosphere deformation processes and were used as a foundation for the early models of basin formation.

One of the first numerical models to link deformation of the continental lithosphere to extensional basin formation, using a kinematic approach was the McKenzie or uniform lithosphere extension model (McKenzie 1978). This model, which is shown diagrammatically in Figure 1a, assumes that the whole of the lithosphere deforms by a pure shear or stretching mechanism quantified by the β or extension factor, equivalent to 1 plus the strain. The McKenzie model is essentially 1D in that it generates results in the form of subsidence curves (Fig. 1b), which show the rift and post-rift phases that characterize many extensional sedimentary basins. The rift phase is caused by the combined effects of crustal thinning, rift-induced heating owing to raising of the lithosphere–asthenosphere boundary and isostatic compensation. It is followed by the post-rift or thermal subsidence phase primarily driven by the gradual cooling of the lithosphere back to an equilibrated state. The McKenzie model and various derivatives, such as the non-uniform lithosphere extension model (Royden & Keen 1980; Hellinger & Sclater 1983), have been applied to many extensional basins in the geological record (e.g. Barton & Wood 1984) and can explain successfully the subsidence history of those basins that have experienced a relatively uncomplicated evolution of rifting followed by gradual post-rift/thermal subsidence.

There was another significant period of advancement in lithosphere-scale modelling during the mid–late 1980s, which was mainly driven by new insights into crustal and upper mantle structure being gained from the acquisition and interpretation of deep seismic data. For example, deep seismic reflection data acquisitioned by the BIRPS group from the United Kingdom (e.g. Brewer & Smythe 1984; BIRPS & ECORS 1986) reveals the important role played by crustal faults during basin formation. The importance of faulting in lithosphere-scale deformation was further emphasised in a qualitative model presented by Wernicke (1985). This model, which is mainly based on observations made from the Basin & Range province in the western United States, assumes lithospheric deformation to be controlled by brittle failure and faulting (i.e. simple shear) in the form of a large-scale shear zone that propagates through the entire lithosphere with a dip at a low angle. The model, therefore, effectively divides the lithosphere into an upper hanging-wall plate and a lower footwall plate. As a result of simple shear, upper crustal (thin-skinned) deformation is spatially offset from zones that have experienced significant lower crust and mantle thinning. Consequently, the model predicts that a basin should be characterized by absent or minimal thermal subsidence in the region that has experienced significant upper crustal deformation. The major weakness of this model is that it fails to account for basins that have post-rift thermal subsidence sequences overlying the regions of major fault controlled subsidence.

Deep seismic reflection data (e.g. Snyder & Hobbs 1999), along with studies of lithosphere deformation (Wernicke 1985), lithosphere rheology (e.g. Kusznir & Park 1987) and seismological investigations (Jackson & McKenzie 1983), have been very important in revealing the large-scale layering and structure of the continental lithosphere within various tectonic regimes. In addition, these studies suggest that lithosphere extension occurs as a hybrid of fault-controlled deformation within the brittle layer of the crust and pure shear extension within the lower crust and mantle lithosphere that

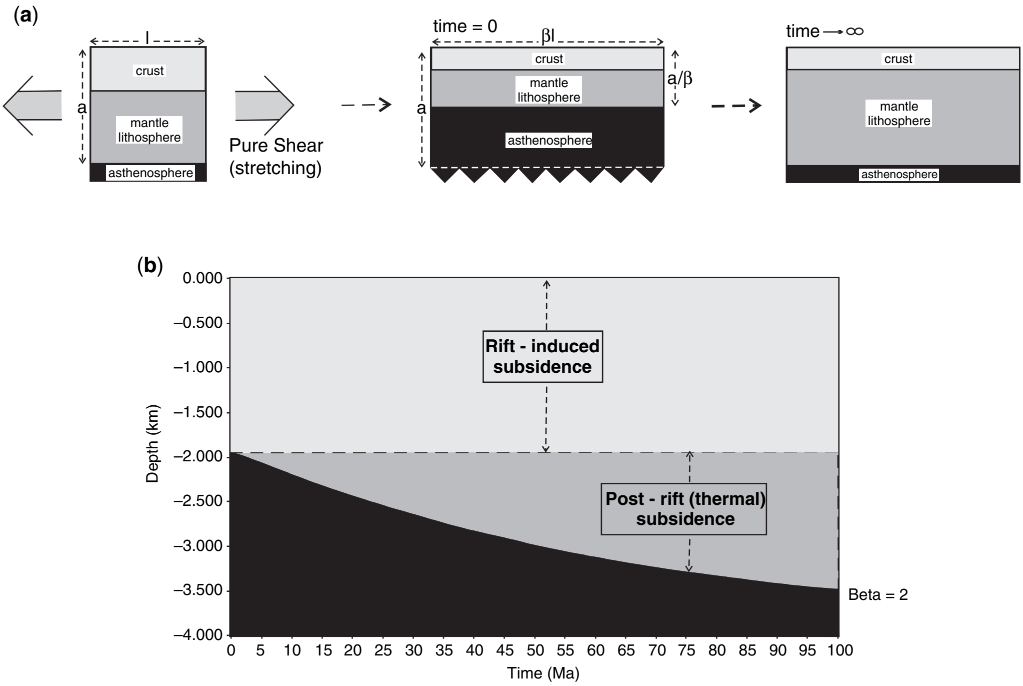

Fig. 1. The uniform lithosphere extension model (McKenzie 1978). (**a**) The model assumes that the lithosphere extends by pure shear and quantifies subsidence owing to crustal thinning and uplift caused by the raising of hotter material at depth nearer to the surface, along with the associated Airy isostatic compensation. The second part of the model simulates the thermal subsidence phase of basin evolution. (**b**) Subsidence curve generated by the McKenzie model showing basin depth following 100% lithosphere extension (i.e. β factor = 2).

dominantly exhibit ductile rheological behaviour (Coward 1986; Kusznir *et al.* 1987). The next section describes how these developments have been extended in improved kinematic models that account more satisfactorily for the evolution of sedimentary basins.

Integrated kinematic modelling of lithosphere extension and compression

This section describes the major processes that occur during lithosphere extension and compression along with some of the approaches that are used to numerically model them. These processes are then integrated into a kinematic model of continental lithosphere deformation.

Mechanical thinning or thickening of the crust owing to movement along crustal faults

Extensional movement along crustal faults generates the foundations of basin structure. It also causes crustal thinning and, therefore, negative loading of the lithosphere, which responds by flexural isostatic rebound. In contrast, reverse movement along crustal faults generates increased surface topography (i.e. crustal thickening) as well as constituting a downwards-acting load on the lithosphere, which responds by flexural isostatic subsidence. Fault configuration within the model is defined in terms of the number of faults required, and their relative spacing and orientation (i.e. synthetic or antithetic). All of the faults are assumed initially to terminate or detach at mid–lower crustal levels in order to maintain compatibility with evidence from deep seismic reflection data (e.g. Hall *et al.* 1984; BIRPS & ECORS 1986), seismological investigations (e.g. Jackson & McKenzie 1983) and rheological modelling of the lithosphere (e.g. Kusznir & Park 1987).

There are several methods, mainly based on geometric constructions, that can be used to simulate deformation caused by fault movement. One the most popular of these constructions is the vertical shear or Chevron construction (Verrall 1982). It assumes that each vertical thickness of hanging wall is displaced laterally by the same amount of extension, usually defined in terms of a heave value. The next assumption is that any unsupported part of the hanging wall following extension deforms such that it collapses directly downwards onto the underlying fault and footwall, which are assumed to be rigid. Geometric methods such as the Chevron construction and derivatives, like the inclined shear method (White *et al.* 1986), are very suitable for numerical modelling applications because they give reasonably accurate results for lithosphere-scale deformation and are computationally efficient.

Mechanical thinning or thickening of both crust and mantle lithosphere by a regionally distributed pure shear mechanism

Although the deformation caused by fault movement plays an important role during lithosphere deformation, seismic data and rheological studies indicate that the lithosphere is mostly too ductile below depths of about 15–20 km to support major fault structures. Instead, the lower crust and parts of the mantle are thought to deform by movement along a network of shear zones that split and merge over relatively short distances (e.g. Reston 1988). One approach that can be used to model this type of regionally distributed deformation is pure shear, stretching under extension and squashing under compression (Kusznir *et al.* 1987). Both the lateral position and the width of the pure shear deformation can be defined in the model. The overall deformation by both faulting and pure shear is initially area balanced in the profile in order to avoid mass balance problems.

Disturbances caused to the lithosphere temperature field

Lithosphere extension and compression causes an overall heating and cooling, respectively. For example, reverse movement along crustal faults causes the emplacement of relatively hot hanging-wall material onto that of a cool footwall, creating a cooling of the geotherm at shallow depth. Compressional deformation by pure shear thickens the lithosphere and also reduces the geothermal gradient. Within the model the lithosphere temperature field is represented as a 2D or 3D grid. Each node on the grid is assigned a predeformational temperature. The temperature of each grid node is then modified according to the amount of deformation experienced.

Re-equilibration of the temperature field after deformation

The lithosphere temperature field experiences gradual thermal recovery after a major tectonic event. For example, in the context of extension the lithosphere cools back to an equilibrated state. The model calculates both lateral and vertical heat flux by the mechanism of conduction. The physical properties of the lithosphere are such that the thermal recovery process takes of the order of 100 million years but follows an exponential decay path.

Flexural isostatic compensation of tectonic loads

Crustal thinning and thickening, and thermal perturbations caused by tectonic activity, impose loads on the lithosphere that have to pass through an isostatic filter to give a compensated amount of subsidence or uplift observed at the surface. The flexural isostatic response of the lithosphere to loading is calculated within the model in order to generate a realistic surface or basement profile and underlying crustal structure. The methodology used to model flexure assumes that the lithosphere behaves as a continuous elastic plate, which is in equilibrium under the action of all applied loads (Turcotte & Schubert 2002). The flexing properties of the lithosphere are defined by its flexural rigidity (Walcott 1970; Watts 2001), which is, in turn, set in the model by the parameter effective elastic thickness (T_e).

Surface processes

The model contains simple algorithms to simulate basin infill and the erosion of uplifts. Isostatic adjustments are calculated in response to these processes such that sedimentary infill enhances subsidence within a basin, whereas erosion has the combined effect of reducing the size of the uplifts and unloading the lithosphere, which responds by regional isostatic uplift or rebound (Egan & Urquhart 1993).

A comprehensive description of all theoretical aspects of the above model are presented in Kusznir & Egan (1989) and Egan & Urquhart (1993), and will not be repeated here. Figure 2, however, illustrates some of the parameters included in the model calculations and examples of results. A typical starting condition for the modelling is shown in Figure 2a, which illustrates a regional cross-section of undeformed lithosphere. The crustal component of this lithosphere is assumed to be 35 km thick with a density of 2800 kg m^{-3}, while the mantle lithosphere is assumed to be 90 km thick with a density of 3300 kg m^{-3}. The modelled lithosphere is thermally conditioned with an equilibrated geotherm, which has a surface temperature of 0 °C and a temperature at the lithosphere–asthenosphere boundary of 1333 °C. All of these parameters can

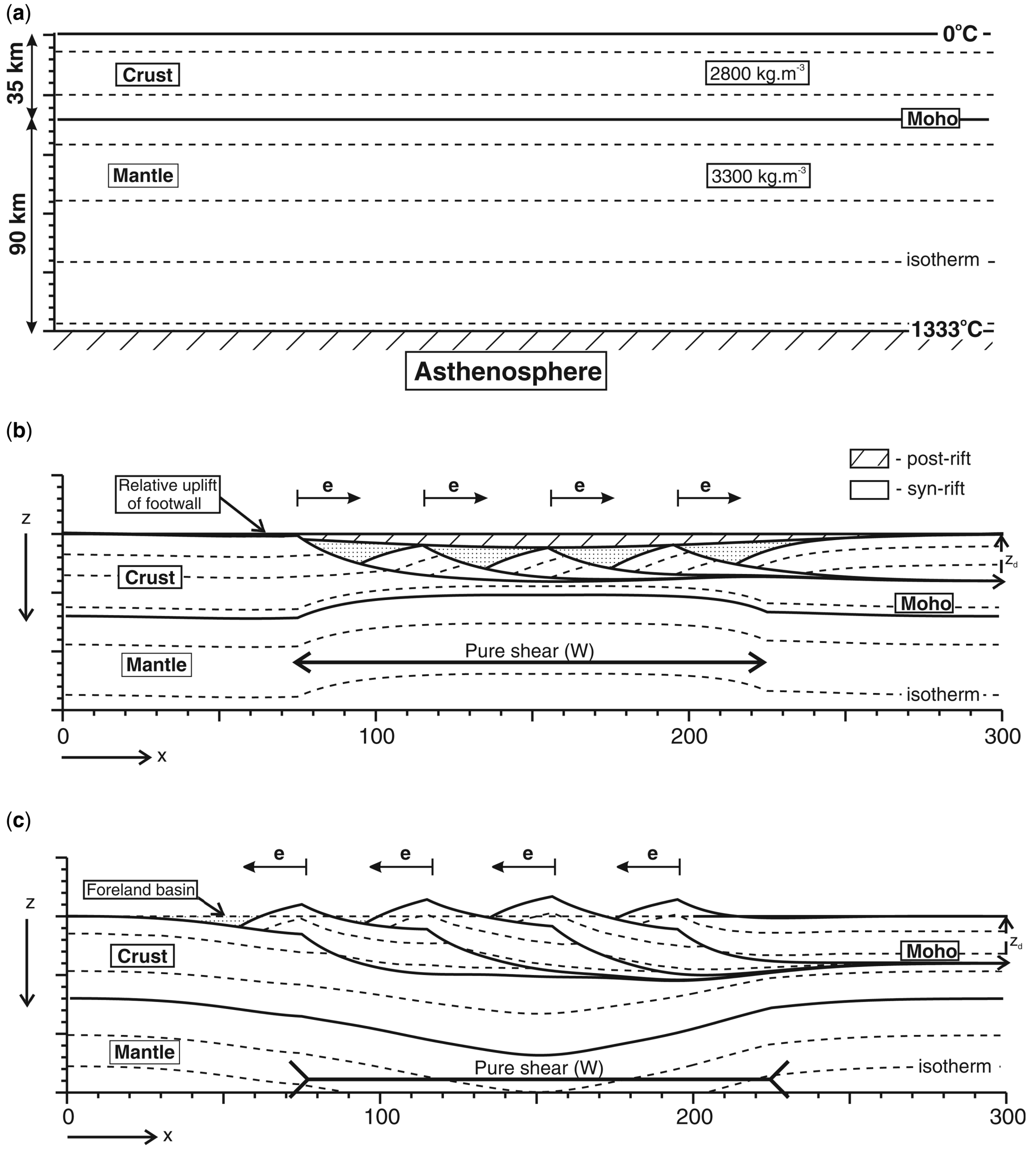

Fig. 2. An integrated kinematic model of lithosphere deformation. (**a**) Cross-section of undeformed lithosphere showing initial values of parameters used in the model calculations. This model can be applied to simulate; (**b**) lithosphere extension and associated basin formation; (**c**) lithosphere shortening and associated thrust-belt and foreland basin formation, or a combination of the two.

be varied according to the tectonic scenario to be modelled.

The effects of extending this lithosphere are shown in Figure 2b. The model shows how the crust has accommodated extensional deformation by movement along a sequence of faults, while the mantle lithosphere has been deformed by regionally distributed pure shear. The boundary between upper crustal deformation and that in the lower crust and mantle lithosphere is determined by a detachment depth, which is equivalent to the concept of necking depth presented by other authors (e.g. Kooi *et al.* 1992). The model shows a basement profile consisting of a sequence of closely spaced half-grabens with relative uplift of the footwall owing to flexural isostatic processes

(Weissel & Karner 1989; Egan 1992). Extension has also caused heating of the lithosphere, which subsequently has cooled to generate gradual subsidence. The effects of this can be seen in the model by a post-rift stratigraphic sequence that blankets the underlying fault blocks and synrift sequence.

Lithosphere shortening is represented by the model in Figure 2c, which shows a 'piggy-back' style of thrusting adjacent to a foreland basin that has been generated mainly by flexure in response to crustal thickening caused by compressional tectonics. In addition, the model is sufficiently versatile to include multiple extensional and compressional events.

Application of integrated kinematic modelling of lithosphere extension and compression to investigate possible subsidence mechanisms within the Black Sea basin

The modelling approach described in the previous section has been applied to the Black Sea, which is a deep, semi-isolated marine basin located north of Turkey and south of Ukraine and Russia. The main aim of the work described in this section has been to use kinematic modelling to try and decipher the role of the main subsidence mechanisms within this poorly understood basin.

An overview of the regional structure and stratigraphy of the Black Sea basin

The Black Sea basin covers an area of approximately 423 000 km^2, has a present maximum bathymetry of 2200 m and comprises the western and eastern Black Sea sub-basins, which are separated by the Mid-Black Sea high (Fig. 3). The origins of the basin go back to a phase of back-arc extension during the mid-late Cretaceous when northwards subduction was occurring beneath modern-day Turkey representing the closure of Tethys Ocean (Hsü 1977; Letouzey *et al.* 1977; Zonenshain & Le Pichon 1986; Görur 1988; Okay *et al.* 1994). Extension continued throughout the upper Cretaceous, perhaps leading to continental separation and the formation of oceanic crust. However, most of the 12–14 km of subsidence experienced by the central parts of the basin took place when the surrounding regions were experiencing compressional deformation. This is demonstrated by Alpine–Himalayan thrust belts, including the Pontides, Balkanides, Crimean Mountains and Greater Caucasus (Fig. 3), that surround the Black Sea.

Regional cross-sections are presented (see Fig. 3 for location) to illustrate the structure and stratigraphy within the western and eastern Black Sea basins. The section presented in Figure 4a shows structure and stratigraphy from offshore Turkey into the centre of the western Black Sea. It is a section constructed from the depth-converted interpretation of a regional seismic line acquired by BP and TPAO. Interpreted horizons have been constrained by data from a well (Akçakoça-1) located in the southern part of the section, which penetrated down into rocks of Cretaceous age at a depth of about 2000 m. The original seismic data are confidential, but a detailed description of its interpretation and analysis can be found in Robb (1998). The cross-section is dominated by major extensional faults, generated by an Albian–Aptian rift phase, which has produced half-graben structures separated by areas of relative footwall uplift. Görür (1988) relates this rift phase to the opening of the western Black Sea due to back-arc extension overlying a northerly dipping subduction zone. However, the magnitude of extension associated with this rift phase was not very great and amounts to about 3 km of heave on the faults observed in the section (approximately 2% overall extension). The deposition of middle–upper Cretaceous synrift sequences was followed by a broad, thin blanket of Paleocene deposits, which from its general distribution is interpreted as a post-rift thermal sag phase. The section becomes more complicated in the Eocene with the contractional reactivation of extensional faults and the development of new reverse faults at the basin margin. In contrast, the northern part of the cross-section shows that the centre of the Black Sea was subsiding very rapidly from the Palaeogene to the present, with the deposition of over 12 km of sediment.

The Ukrainian Black Sea region is dominated by basin inversion as shown by the section in Figure 4b. The sequence of tectonic events that have generated the overall structure and stratigraphy exhibited in this section are, however, very similar to those already described in the context of the Turkish section. Again, there is evidence of rifting during the middle Cretaceous. The extensional evolution of this part of the basin was terminated during the Eocene by an inversion phase. Inversion continued into the Oligocene, generating uplift and erosion of the earlier syn- and post-rift sequences. A foreland basin-type sequence was generated in the Miocene as a response to the crustal thickening and flexure caused by the inversion tectonics. Finally, the Neogene sequence indicates a dramatic increase in subsidence towards the centre of the Black Sea, which has also caused the proximal parts of the shelf to subside flexurally.

The deeper structure of the western Black Sea basin is a matter of controversy because of an

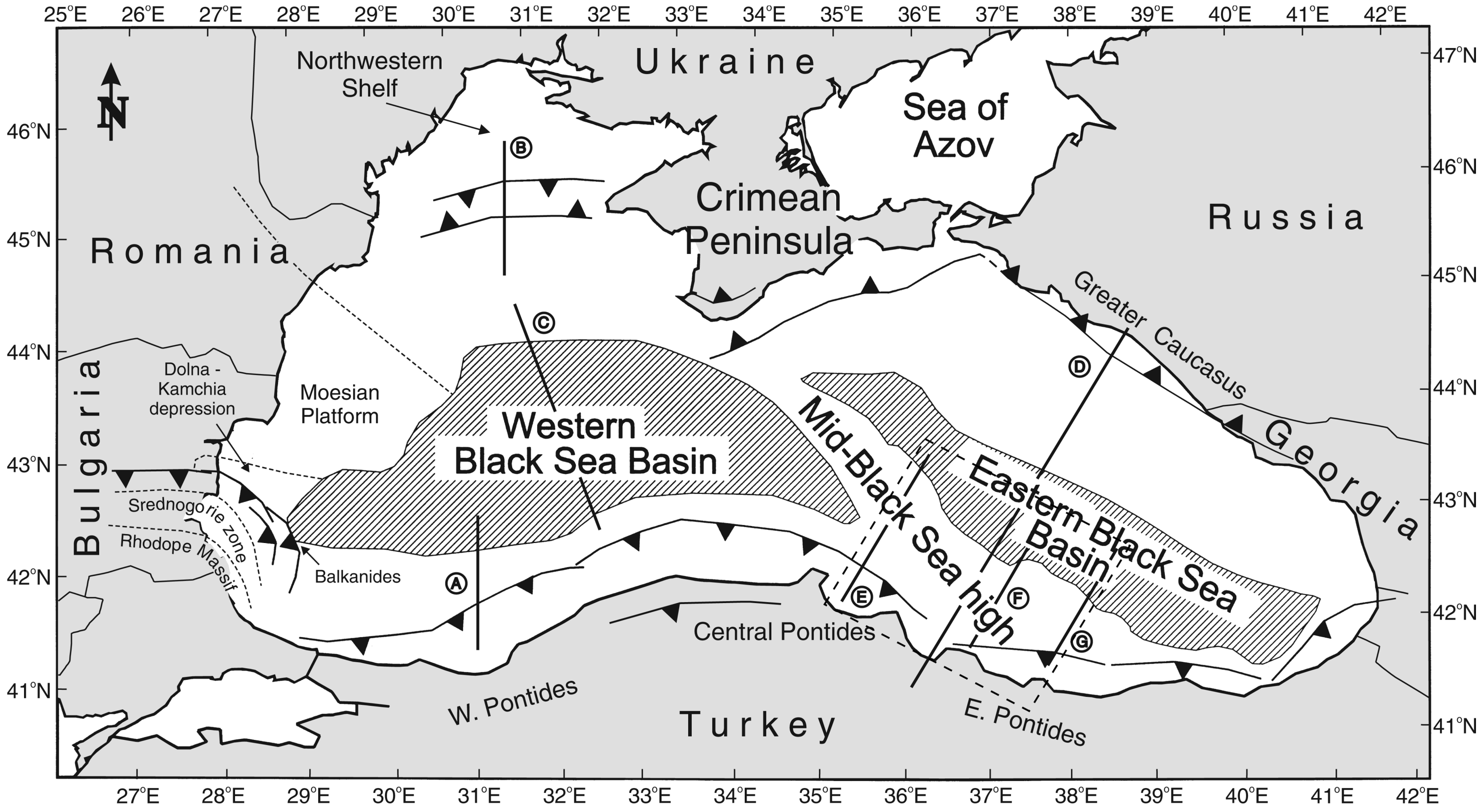

Fig. 3. Black Sea location map showing major tectonic elements (adapted from Robinson 1997) and location of cross-sections used for modelling study of the basin. The rectangle positioned within the eastern Black Sea shows the approximate extent of the 3D model (see Figs 10 & 11).

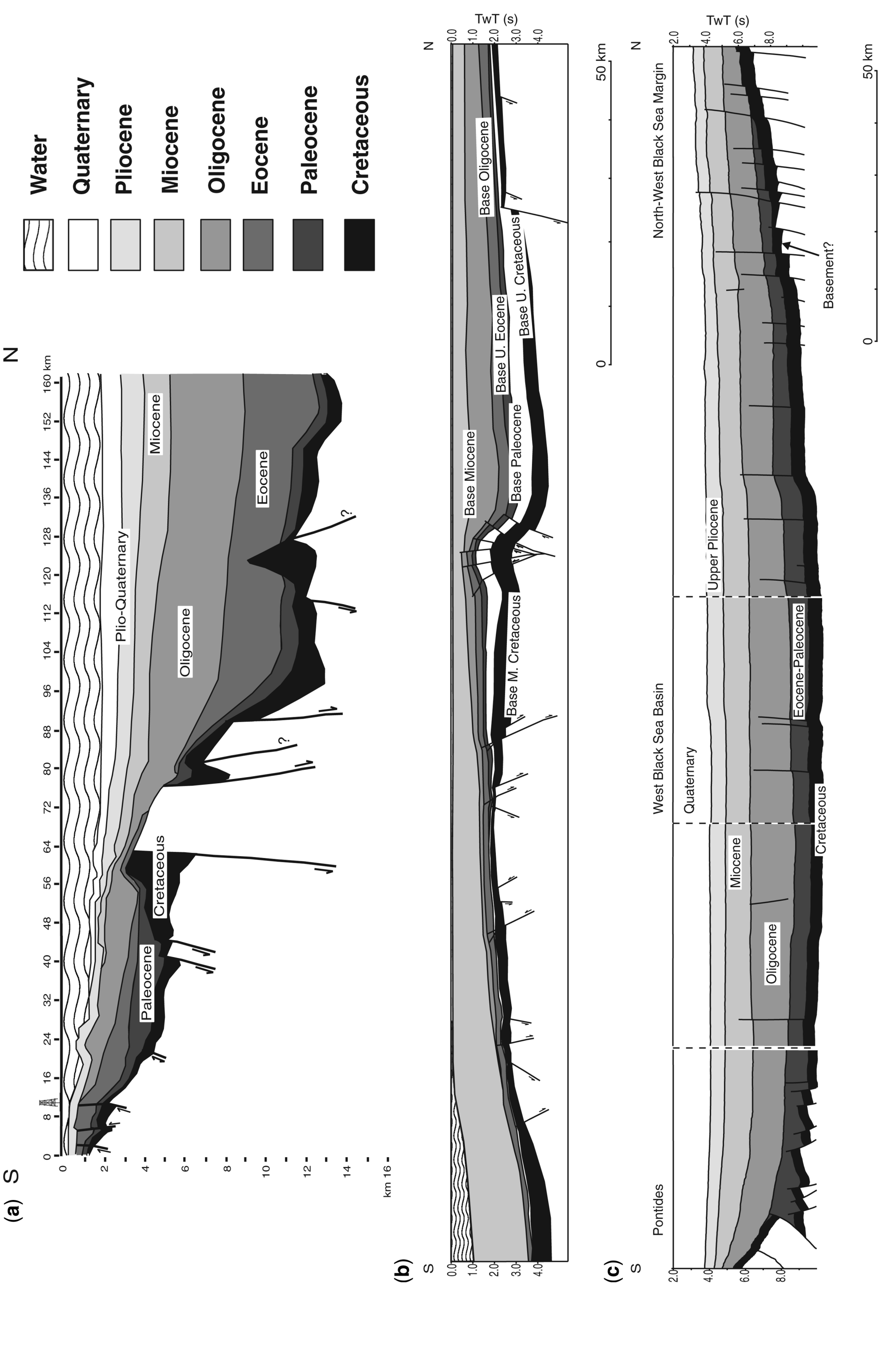

Fig. 4. Sections showing structural and stratigraphic components across the western Black Sea (see Fig. 3 for location information). (**a**) Depth section across the Turkish part of the basin. (**b**) Two-way time (TWT) section across the Ukrainian part of the basin. (**c**) Composite TWT section across the central (western) Black Sea (adapted from Finetti *et al.* 1988) based on the interpretation of several regional seismic lines (vertical dashed lines indicate the boundaries between the individual seismic lines).

absence of well data and inadequate seismic reflection data at depth. The section presented in Figure 4c illustrates the overall structural and stratigraphic style in the central part of the basin, and is based upon interpreted seismic data presented by Finetti *et al.* (1988). This section shows that the central western Black Sea basin is characterized by a flat-lying sedimentary sequence, which reaches depths of about 14 km. Although the seismic data do not show deep structure, Finetti *et al.* (1988) suggested that the basin-fill sequence has been deposited on flat-lying basement, probably basaltic in composition. Evidence from gravity and seismic refraction data (Neprochnov *et al.* 1970; Belousov 1988) also suggests that western Black Sea basement may consist of oceanic crust. There is, however, no direct evidence as to whether the density structure determined from these data is due to oceanic crust or to highly attenuated and/or metamorphosed continental crust.

Four regional-scale sections across the eastern Black Sea are presented in Figure 5 (see Fig. 3 for locations). These sections are derived from the interpretation of seismic reflection lines acquired by BP and TPAO that have been interpreted by BP personnel and subsequently modified (Meredith & Egan 2002). The original seismic data are confidential. Section D (Fig. 5a) shows structure and stratigraphy from onshore Turkey, into the centre of the eastern Black Sea and finally onto the Russian shelf in the NE of the region. As for the western part of the basin, the section is dominated by extensional faults. In particular, the Archangelsky and Shatsky ridges represent regionally uplifted footwall blocks to extensional faults that form the southern and northern continental slope regions, respectively. This interpretation is in agreement with Banks *et al.* (1997), who suggest that the Shatsky ridge defines the northern rift margin of the eastern Black Sea. Similar to the western Black Sea, fault displacement measurements indicate that the magnitude of extension was not very great and amounts to about 60 km of heave on the faults observed in section D. This equates to an overall magnitude of extension of approximately 13% (i.e. $\beta = 1.13$). Thickness variations across the oldest horizons in the section suggest that rifting occurred later than in the western sub-basin, possibly some time in the Paleocene or Eocene. This timing correlates with a late Paleocene–early Eocene rift event suggested by Banks & Robinson (1997) and Spadini *et al.* (1997), or early–middle Eocene rifting inferred by Kazmin *et al.* (2000).

The onshore and shelf regions of the eastern Black Sea become more complicated at the end of the Eocene with evidence of compressional deformation. Compressional tectonic features are best developed in the NE part of section D (Fig. 5a) where the Tuapse fold belt, which forms the southern limit of the Great Caucasus mountain belt, shows reverse movement along basement faults. Immediately adjacent to this thrust belt is the Tuapse Trough, which is superimposed onto the footwall block forming the Shatsky ridge. The deeper structure of the central part of the eastern Black Sea basin is a matter of controversy because of the general poor quality of seismic reflection data at depth. The sections presented in Figure 5 show a similar structural and stratigraphic style to the western Black Sea in that the central part of the basin is characterized by a ‘layer-cake’ stratigraphy, which is present to depths of over 12 km.

The western Black Sea basin – application of a 2D kinematic approach

The three cross-sections described in Figure 4 have been combined to produce a regional cross-section that extends from the Ukrainian to Turkish margins of the western Black Sea (Fig. 6). Possible processes that have contributed to the subsidence history exhibited by this section are explored below using the kinematic modelling approach described in the previous section on ‘Integrated kinematic modelling of lithosphere extension and compression.’

Has the western Black Sea evolved due to uniform lithosphere extension combined with loading from the surrounding thrust belts? Figure 7 shows a model of the western Black Sea using the methodology described in the previous section. The overall dimensions of the model, along with major fault structures, are based upon the regional north–south section across the western Black Sea presented in Figure 6. In addition, deformation by faulting has been balanced to regionally distributed stretching at depth to represent uniform lithosphere extension. The model results show clearly that it is not possible to reproduce Black Sea subsidence with extensional deformation constrained by the magnitude of faulting. The magnitude of observed deformation as determined from extensional movement along fault structures amounts to 6.75 km total heave (equivalent to β of approximately 1.01) across the section. In addition, this deformation is mainly confined to the basin margins and can only account for overall subsidence in these parts of the basin. However, the model shows less than 1 km of subsidence in the central part of the basin, which is mainly produced by thinning of the lower crust, thermal subsidence (modelled for a 100 million years time period) and sediment loading in response to pure shear deformation. This amount falls far short of the 14 km of total subsidence indicated by seismic data.

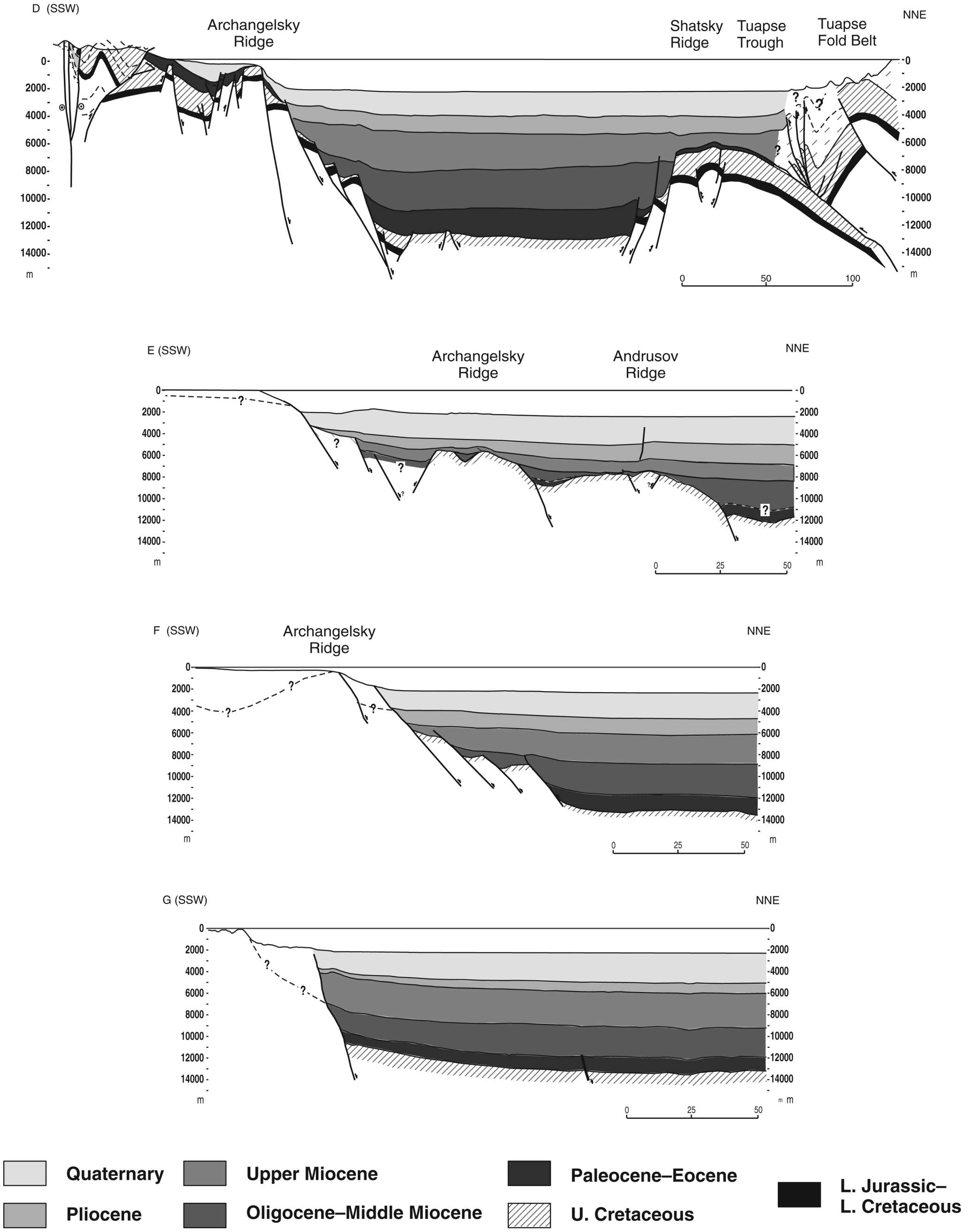

Fig. 5. North–south sections across the eastern Black sea (see Fig. 3 for locations) showing a dominance of compressional tectonics within the Turkish and Russian onshore and near-shelf regions. Extensional tectonics dominates both northern and southern continental slope regions. The deep basin, however, shows a thick, flat-lying sedimentary sequence that is mostly devoid of structure.

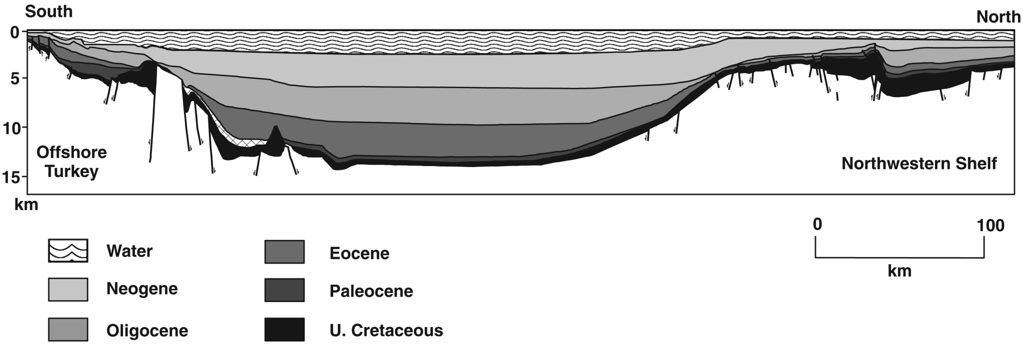

Fig. 6. Composite section (adapted from Robb 1998) across the western Black Sea based on the combination of the individual sections presented in Figure 4.

It is possible that a significant component of post-rift subsidence was caused by compressional tectonics. More precisely, the loading generated by the thrust belts surrounding the Black Sea may have caused the development of foreland basins, which constructively interfered to produce one large basin. Cobbold (1993) refers to this type of structure as a 'push-down basin,' while Graham (1995) calls them 'Central Asian type basins,' which have the characteristics of being 'relatively symmetric, relatively fixed and commonly contain enormous thicknesses of sediment.'

The effects of loading from surrounding thrust belts have been modelled in the context of the western Black Sea. The model profile presented in Figure 7c represents the extensional evolution of the basin followed by compression at the margins occurring at a modelled time of 50 Ma to represent the onset of deformation due to the Alpine–Himalayan orogeny. The magnitude of both extensional and compressional deformation is constrained by the fault movement measured from the cross-sections in Figures 4 & 6. A lack of data prevents widening of the model to reproduce compressional deformation observed in the Pontides and Ukraine. However, it is very evident that the flexural subsidence generated in response to the formation of the thrust belts deepens the original extensional basin at its edges, rather than in the centre. The model also shows how crustal thickening has caused uplift of pre-, syn- and post-rift sequences at positions 10 and 500 km along the section. These uplift structures can also be observed in the data, but they are not subaerial. In addition, the model does not generate sufficient flexural subsidence in the centre of the basin.

Crustal thinning beneath the western Black Sea. Although there appears to be a lack of extensional faulting within the western Black Sea, it cannot be discounted that there are more extensional faults than resolved by the seismic data and that the magnitude of deformation assumed within the models presented so far is an underestimation. The model results presented in Figure 8 are also based on uniform lithosphere extension. However, the magnitude of extension has been increased significantly compared to the models presented in Figure 7. This is because the magnitude of deformation has been calculated using crustal thickness rather than basement faulting. The cross-section presented in Figure 8a has been adapted from that in Figure 6 to show the relative thickness of syn- and post-rift stratigraphy. The boundary between these sequences is placed at the division between the Cretaceous and Paleocene, as shown in Figures 4 & 6. The section also shows an estimation of the depth to basement (i.e. base synrift). Although this boundary cannot be accurately determined from the data available, it is assumed to occur at the base of the Upper Cretaceous (Görür 1988; Spadini *et al.* 1996). An estimation of Moho topography is also displayed and is based on commercial gravity data and published material (e.g. Neprochnov *et al.* 1970, 1974; Belousov 1988). The prerift thickness of the crust in the Black Sea region is open to debate. However, Spadini *et al.* (1996) propose that the western Black Sea formed by the rifting of the Moesian-European platform, which has a characteristic crustal thickness of 35 km.

From the section presented in Figure 8a it is possible to determine the magnitude of crustal thinning or thickening relative to a regional average and, in turn, to calculate a sequence of β values (i.e. 1 + strain: McKenzie 1978) across the basin. This β distribution has been used to constrain the magnitude of extension and compression evident in the model presented in Figure 8b, which assumes uniform deformation of the lithosphere based entirely on a pure shear mechanism. The

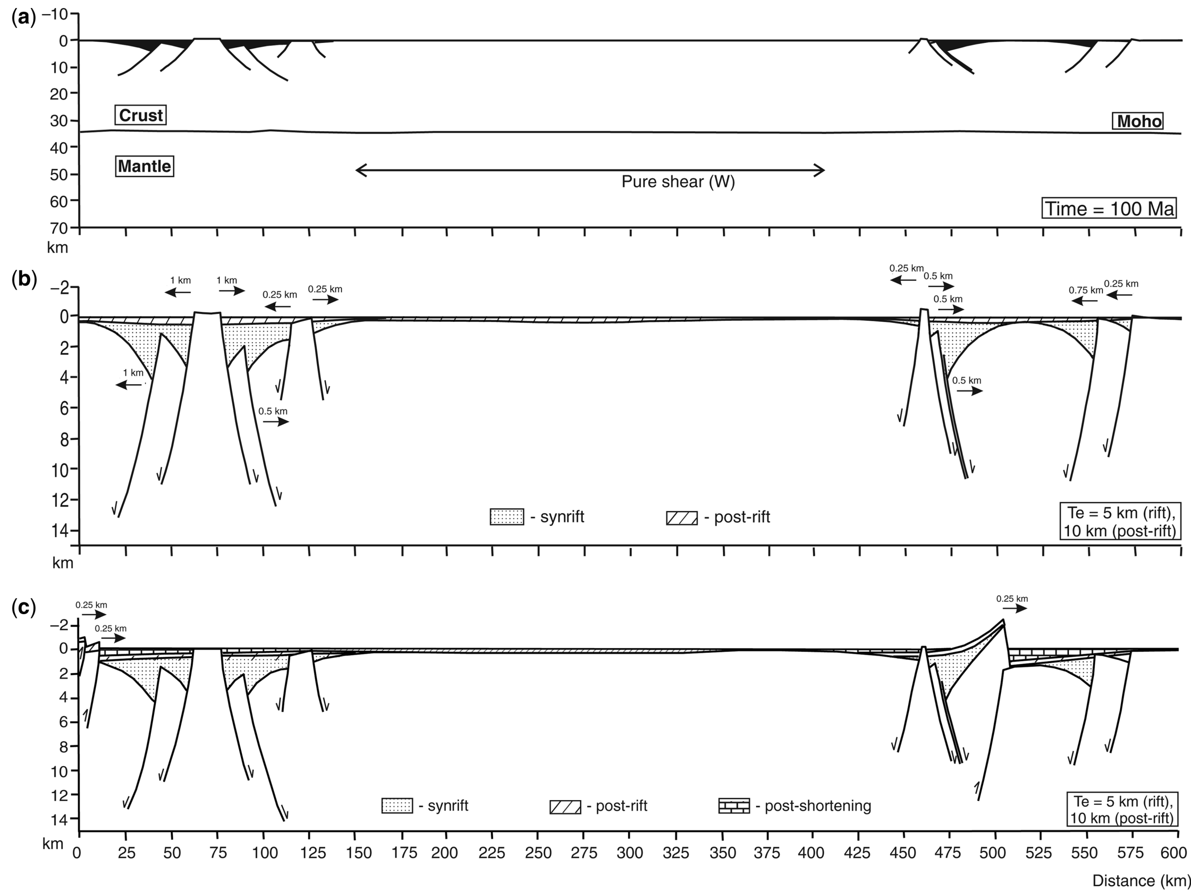

Fig. 7. Model profile based on the cross-sections presented in Figures 5 & 6. (**b**) is a vertical exaggeration of (**a**) to show the details of basin structure and its infill. The model represents uniform lithosphere extension, whereby deformation by faulting is balanced to regionally distributed stretching at depth. Although it is possible to explain the overall magnitude of subsidence at the basin margins by this mechanism, model results show that it is not possible to reproduce the large amount of subsidence observed in the central part of the basin. (**c**) Model profile investigating the possibility that Black Sea subsidence can be explained by loading caused by adjacent thrust belts.

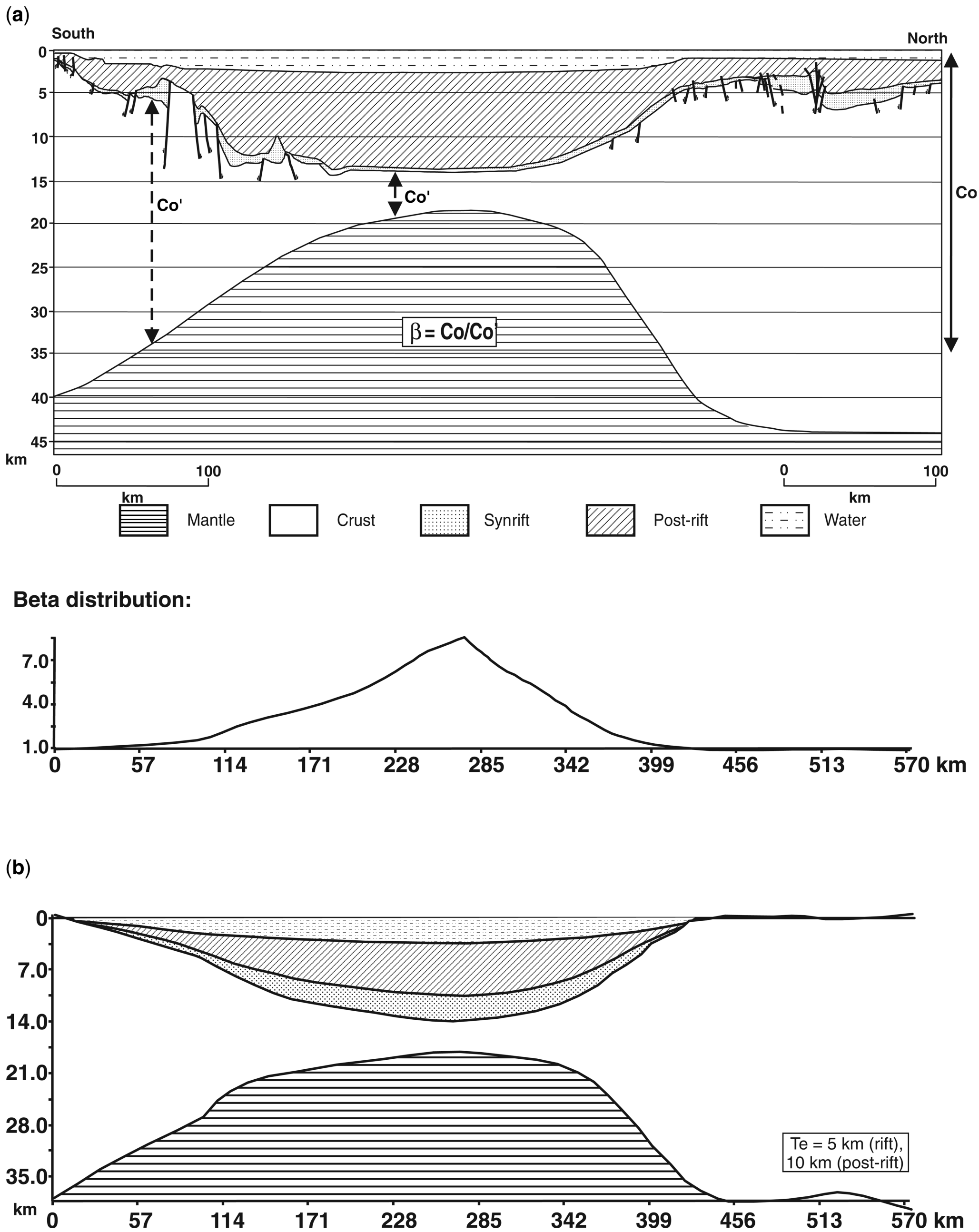

Fig. 8. (**a**) Cross-section adapted from Figure 6 to show syn- and post-rift stratigraphy, top basement and Moho depth. Thinning or thickening of the crust (Co′), relative to a regional average of 35 km (Co), has been used to quantify the magnitude of deformation across the profile in terms of a β distribution. (**b**) Model based on the magnitude of deformation calculated in (a) assuming uniform lithosphere deformation. The model shows overall subsidence that is comparable with that observed in the western Black Sea. However, the relative thicknesses of syn- and post-rift sequences do not match observations.

model shows an overall basin depth that is almost comparable with that across the western Black Sea. Maximum subsidence predicted by the model is 13.5 km. The value of elastic thickness for the Black Sea region at the time of rifting and during post-rift evolution is open to speculation. Model calculations have assumed an effective elastic thickness (T_e) of 5 km at rifting and 10 km for the post-rift phase based on a sensitivity test of the parameter in terms of it generating the most realistic combination of basin geometry and subsidence. These values are also compatible with a number of rift settings (e.g. Barton & Wood 1984; Kusznir *et al.* 1991; Van Wees & Cloetingh 1994). Although the model includes the effects of infilling the basin with sediment (density = 2500 kg m^{-3}), a bathymetry, rising to a maximum depth of 3 km in the centre of the basin, has been maintained so as not to overestimate the loading and subsidence caused by sediment infill. The main difference between the model profile and observed data concerns the proportions of syn- and post-rift stratigraphy. The model shows a synrift sequence that reaches a thickness of 3.5 km. This value is not compatible with the data interpretation in Figure 8a, which suggests that the basin fill is mainly post-rift and that the synrift sequence is of the order of 1–2 km in thickness.

Possible effects of subsurface loading. In this subsection we investigate the possibility as to whether the subsidence history of the western Black Sea basin can be explained by depth-dependent extension, such that the deformation of the mantle lithosphere by stretching exceeds that in the crust due to faulting. The importance of depth-dependent stretching was identified by the numerical modelling of two-layer lithosphere stretching carried out by Royden & Keen (1980) and Hellinger & Sclater (1983). More recently, depth-dependent stretching has been used to explain the discrepancies between upper and lower lithosphere extension within continental margin settings (e.g. Roberts *et al.* 1997; Kusznir *et al.* 2004).

The model profiles presented in Figure 9 have again used a faulting configuration based on the regional north–south section across the western Black Sea, but the extension has been increased in the lower crust and mantle lithosphere (i.e. below the assumed detachment depth at 20 km). The model presented in Figure 9a has assumed extension in the lower crust and mantle lithosphere to be given by a maximum β value of 8.5 (at $x = 300$ km), which is compatible with the overall magnitude of crustal thinning. β is decreased following a sinusoidal distribution to no deformation over a lateral distance of 210 km either side. The pattern of subsidence exhibited in this model is similar to that exhibited in the regional section. More specifically, the model shows a very thin synrift phase, analogous to the small thickness of middle–upper Cretaceous synrift deposits observed in the basin, and a large thickness of post-rift deposition, analogous to the thick Palaeogene and Neogene sequences observed in the basin. However, overall basin depth is too shallow compared to the observed data for the basin.

The modelling approach used to generate Figure 9a assumes a fixed detachment depth of 20 km, whereby the upper crust above this depth is thinned by faulting as observed from the data, while the lower crust is thinned by pure shear according to the estimated thinning of the crust (see Fig. 8a). The assumption of a fixed detachment depth limits the magnitude by which the crust can be thinned overall and explains the relatively low basin subsidence generated in the model profile. The model presented in Figure 9b attempts to reconcile the observed magnitude of fault-controlled extension with the observed attenuation of the whole crust. The scenario modelled is one where the detachment or necking depth is allowed to progress towards the surface rather than being fixed at mid-crustal levels. The detachment zone may migrate throughout the evolution of a rift or during multiple rifts because the thickness of the brittle and ductile zones would constantly change during deformation in response both to the changing thickness of the crust and to temperature perturbations (Kusznir & Park 1987). In addition, Driscoll & Karner (1998) show an example of how an east-dipping detachment model of the northern Carnarvon Basin, Australia has been used to account for the observed discrepancy between the amount of upper crustal and lower lithosphere deformation. The model presented in Figure 9b shows how thin early fault-related synrift sediments are generated during an initial stage of rifting. Depth-dependent stretching then thins the crust (from its base) during a second rift stage. Maximum basin subsidence is about 13.5 km, which is comparable to that observed in the western Black Sea. Similarly, the model exhibits a very thin synrift stratigraphic thickness, large post-rift thickness and a realistic bathymetry. These results suggest that enhanced mantle extension may have played a role in the evolution of the western Black Sea.

The eastern Black Sea basin – application of a 3D kinematic modelling approach

A weakness with 2D basin models is that the Cartesian co-ordinate that extends perpendicular to the plane of the section is assumed to be both constant and infinite in extent in terms of its physical

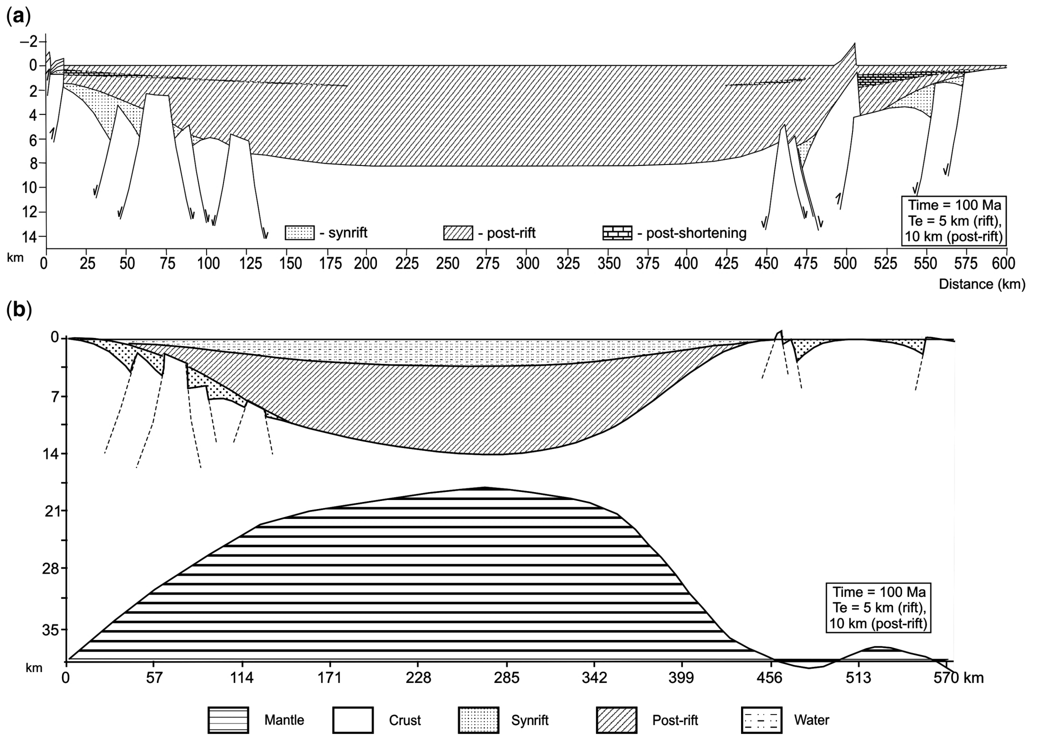

Fig. 9. (**a**) Model based on depth-dependent stretching, whereby the lower crust and mantle lithosphere have been extended more than the upper crust. This model is comparable with the data in that it shows a relatively thin synrift sequence overlain by a thick post-rift sequence. (**b**) Model that reconciles the observed magnitude of fault-controlled extension with the observed attenuation of the whole crust. The scenario modelled is one where the detachment or necking depth is allowed to progress towards the surface rather than being fixed at mid-crustal levels.

properties. As a result, lateral discontinuity in structure and thermal perturbation outside the plane of section is ignored. This has significant implications on the flexural compensation of loads and on the true geometry of the plane of the modelled section. In three dimensions, flexural interactions modify the spatial pattern and extent of basement subsidence and/or uplift. A 3D lithosphere-scale basin model has been developed in order to investigate how regional interactions between a range of geological and geodynamic processes control basin subsidence and stratigraphy through time. This model has been applied to provide insights into the regional subsidence history of the eastern Black Sea.

The methodology developed is similar to that in the 2D modelling whereby a range of parameters can be independently controlled and defined in order to simulate basin development through time whilst accounting for multiple rift phases, progressive sediment infill and reproduction of bathymetry. The following subsection describes this modelling approach and the additional considerations required when modelling geological and geodynamic processes in three dimensions.

- A set of crustal thickness profiles (e.g. Fig. 8a) are constructed initially.
- For each model time step, the tectonically induced subsidence (thermally and mechanically derived) is calculated and flexurally compensated for by assuming an initial water infill. Loading owing to changes in crustal thickness, thermal effects, sediment infill and bathymetry are compensated for by using a 3D flexural algorithm modified after Hodgetts *et al.* (1998).
- Perturbation and/or re-equilibration of the lithosphere temperature field is calculated for each model time step.
- In order to simulate the observed proportion of sediment infill, the basin is then filled with sediment to a potential maximum bathymetry. The extra flexural subsidence generated from the initial sediment infill is then optionally filled

with sediment or water ensuring that variations in the infill density are compensated for at all times.

- If necessary, this procedure is repeated using a different potential maximum bathymetry until an approximate representation of the proportion of sediment infill is obtained. Owing to the lack of data generally available on the regional palaeobathymetry, this method provides an alternative approach to filling the basin to a 'known' palaeobathymetry and also provides an estimate of how the basin's sediment–water interface has evolved through time.

A detailed description of the theoretical aspects of this 3D modelling approach can be found in Meredith (2003).

The cross-sections presented in Figure 5 have been used to provide 'seed-lines' for a 3D model that covers an area of 52 000 km^2 of the Turkish and central regions of the eastern Black Sea (see Fig. 3 for location). A β profile has been calculated for each of the cross-sections based upon variation in crustal thickness. β values have been calculated at 4 km intervals along each profile and, in turn, placed into a 3D spatial model as to coincide with the relative positions of each cross-section. Figure 10 shows a 3D model representation of the eastern Black Sea assuming evolution by uniform lithosphere extension of a 35 km-thick crust. The model has been simulated over a period of 65 Ma. Effective elastic thickness is assumed to be 5 km during instantaneous rifting, evolving to 10 km during the post-rift subsidence phase. The model also reproduces and regionally compensates for temporal changes in both stratigraphic thickness and bathymetry. Post-rift sediments have been subdivided into early- and late-stage sequences in order to replicate the Paleocene–Middle Miocene sequence and the anomalously thick Upper Miocene–Quaternary sequence.

Total subsidence is shallower in the 3D model than is observed. Maximum basin depth is 12 km, whilst maximum depth in the model is 8.5 km. A lack of subsidence is further depicted in the model by the elevation of the Archangelsky and Andrusov Ridges, which, according to the data, have accumulated significant thicknesses of Quaternary sediment. This reduction in basin depth in the 3D model partly results from the increase in out-of-plane flexural support provided by the Mid-Black Sea High. This is illustrated in Figure 10 by the increase in basement elevation when moving westerly toward the Mid-Black Sea high.

Variations in prerift lithospheric configuration, including crustal thickness, can strongly control the total magnitude of subsidence produced during and after extension. Estimation of the prerift crustal thickness remains widely open to conjecture owing to the long succession of rifting and collisional events that have preceded eastern Black Sea basin development. If the prerift crust had been thicker than the commonly assumed thickness of 35 km, the total subsidence derived from the apparent magnitude of extension would be enhanced. According to Sengör *et al.* (1985), the prerift crust of western Turkey was thickened by early Palaeogene compression to an estimated thickness of 50–55 km. Kazmin *et al.* (2000) also propose that the prerift basement of the eastern Black Sea was analogous to that in the eastern Pontides, which is known to have undergone strong Paleocene compression and thickening (Okay & Sahintürk 1997). This evidence suggests that the thickness of the prerift crust may have been in the order of 40–45 km. Consequently, models have been produced in order to investigate rifting of a thickened prerift crust.

Figure 11 shows a 3D model representation of the eastern Black Sea assuming evolution by uniform lithosphere extension of a 45 km-thick prerift crust. Raising the initial crustal thickness value to 45 km produces extension across the whole model and a maximum β value of 4.2 in the central basin. Model results indicate that rifting of a thickened crust generates sufficient subsidence to house the great thicknesses of post-rift sediments including the present-day deep bathymetry. Three-dimensional reproduction of the basin depth, and syn- and post-rift stratigraphic architectures are directly comparable with that observed. In addition, model results suggest that the anomalously thin synrift sediments and thick post-rift sequences could have resulted from underfilling of the basin due to prolonged sediment starvation followed by late stage post-rift sedimentation.

Discussion

There has been much speculation within the literature as to the cause of the large magnitude of subsidence within the Black Sea. In this study we have used 2D numerical modelling of lithosphere extension and compression to test some of the subsidence mechanisms proposed for the western part of the basin. Readers should refer to Meredith & Egan (2002) for the application of a similar approach to the eastern Black Sea. Model results show clearly that it is not possible to explain subsidence in the Black Sea by uniform lithosphere extension coupled with sedimentary infill, when the magnitude of extension is constrained by the observed faulting of basement. Furthermore, it is very unlikely that the lack of extensional structures evident within the central part of the basin can be entirely

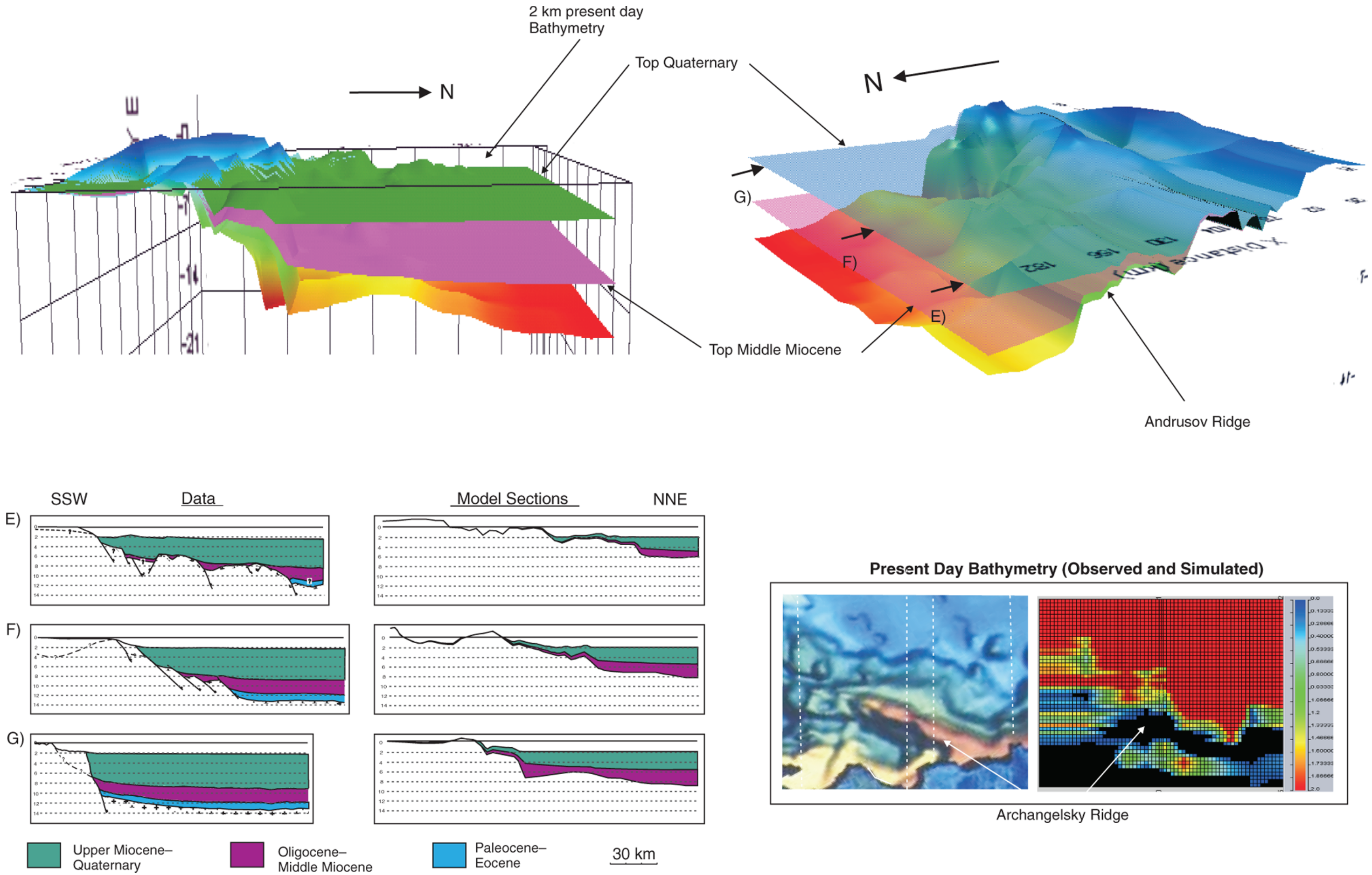

Fig. 10. Application of the 3D kinematical modelling approach to the eastern Black Sea. Extension of a 35 km-thick crust simulates the main structural elements and a syn- and post-rift stratigraphy that has a near-comparable ratio to those observed. The basin model, however, is shallower than observed partly due to the increased flexural support produced by the Archangelsky Ridge, which is orientated obliquely to the direction of the data sections.

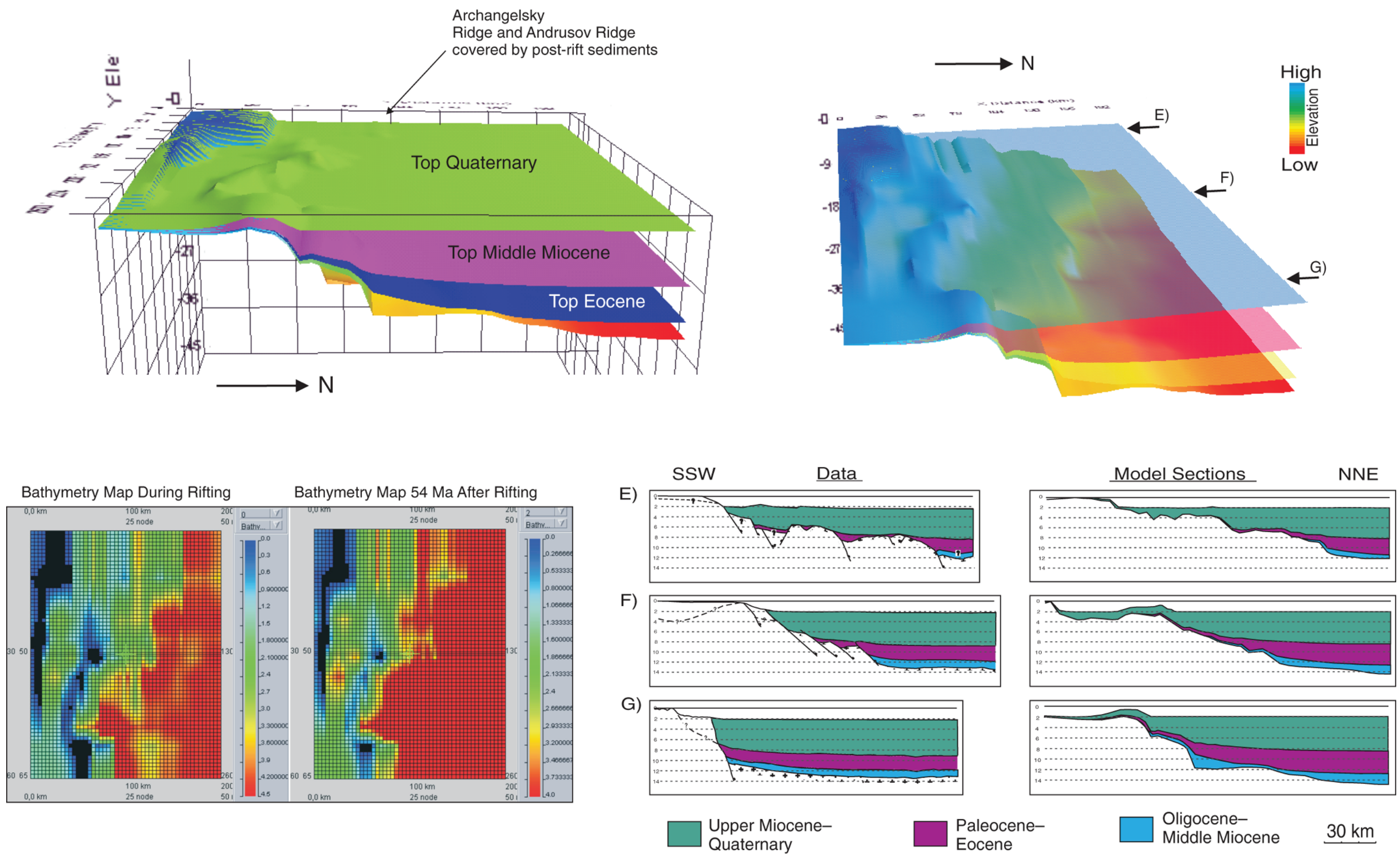

Fig. 11. Three-dimensional model of the eastern Black Sea. Extension of a thicker (45 km) prerift crust maximizes synrift subsidence, and produces a syn- and post-rift stratigraphy that is directly comparable in terms of thickness and architecture to that observed in the eastern Black Sea.

attributed to a lack of resolution within the currently available data. Walsh *et al.* (1991) have shown that typically 10–40% of total fault-related extension may not be observed on regional-scale seismic profiles. However, the difference between magnitude of observed fault controlled extension and overall deformation of the crust is over 200% in the context of the Black Sea.

It is now widely accepted that the relative thickness of syn- and post-rift sequences within a basin can be influenced by the nature of the extensional deformation experienced by the lithosphere. More precisely, the relatively thick post-rift sequence within the Black Sea could be explained by depth-dependent extension whereby the magnitude of deformation within the mid–lower crust and mantle lithosphere is much greater than that experienced by the upper crust. Modelling of this deformational regime (Fig. 9) is compatible with the subsidence history of the Black Sea in terms of the overall magnitude of subsidence as well as generating a relatively small amount of synrift subsidence followed by a much thicker post-rift sequence. It is also compatible with the suggestion that the Black Sea is floored by oceanic crust because enhanced mantle extension raises the lithosphere asthenosphere boundary to a shallow depth resulting in adiabatic melting within the mantle lithosphere and the potential to generate several kilometres of melt thickness (McKenzie & Bickle 1988). It is beyond the capabilities of the modelling used in this study simulate the formation of oceanic crust. In addition, there is little constraint from data or the published literature on how oceanic crust may have formed in the Black Sea region or, indeed, what its relationship is with the surrounding (continental) margins. However, the possible occurrence and mechanisms of generation of oceanic crust within the Black Sea requires further investigation.

The observed discrepancy between the amount of upper crustal extension by fault displacements and overall crustal thinning in a variety of sedimentary basins has been identified by a number of authors (e.g. Moretti & Pinet 1987; Ziegler 1992; Driscoll & Karner 1998; Kusznir *et al.* 2004). Evidence of crustal stretching is often absent or indicates only less than 10–15% stretching (Artyushkov 1992). A number of problems exist with regards to the validity of the enhanced extension mechanism. In particular, space problems arise if there is exaggerated stretching of the lower crust and mantle lithosphere (e.g. Rowley & Sahagian 1986). A number of possible mechanisms may provide a solution to this apparent complication. Royden & Keen (1980) have argued that magmatic intrusion into the crust may account for some of the inherent space problems. According to Brun & Beslier (1996), mantle exhumation at passive margins and in the core complex of intracontinental basins may also accommodate the space problem associated with enhanced extension of the mantle lithosphere. Watcharanantakul & Morley (2000) have also recently argued that enhanced stretching could be accomplished by subduction roll-back and slab steepening of a subducting plate and have applied this mechanism to the syn- and post-rift modelling of the Pattani Basin, Thailand. In addition, lower crustal flow has also been advocated as a mechanism for explaining the observed discrepancy between the amount of upper crustal extension and extent of crustal thinning (e.g. Bertotti *et al.* 2000). At geological timescales, weak ductile lower crust may behave as a ductile fluid channel able to flow from areas of high lithostatic stress to areas of lower lithostatic stress (Block & Royden 1990; Westaway 1998). However, predicting the flow behaviour of the mid and lower crust remains uncertain, and in terms of numerical modelling requires further investigation.

A 3D kinematic modelling approach illustrates the importance of simulating regional-scale basin subsidence and flexure in three dimensions in order to have an appreciation of out-of-plane flexural support of loads. Application of the 3D kinematic modelling approach to the eastern Black Sea suggest that extension of a thickened (40–45 km) prerift crust is necessary in order to generate the necessary amount of subsidence. Indeed, a number of studies support the occurrence of compressional tectonics related to Tethys subduction occurring in the region before the onset of (back-arc) extension. Consequently, it is argued that extension of a continental crust 5–10 km thicker than average is a potential mechanism that may certainly account for the overall subsidence and basin depth.

Summary

A kinematic model of lithosphere deformation has been developed that includes the complex interaction, in two and three dimensions, of structural, thermal, isostatic, rheological and surface processes to simulate the evolution of extensional basins and thrust belt–foreland basin couplets. Application of this kinematic modelling approach to the western Black Sea indicates that it is not possible to reproduce subsidence within the basin when the magnitude of lithosphere extension is based on the amount of fault-controlled deformation. However, modelling of the Black Sea in which the magnitude of deformation is constrained using crustal thinning/thickening generates amounts of total subsidence that are comparable with that observed. These models rely on a depth-dependent extension mechanism to reconcile the observed (small) magnitude of faulting with overall attenuation of the crust. In addition, a 3D modelling approach has been applied to the eastern Black Sea and shows that the magnitude of total subsidence is significantly reduced when accounting for a realistic bathymetry, infill and regional flexure, even when the overall magnitude of deformation is constrained by the observed crustal thinning. The observed subsidence has to be accounted for by additional subsidence mechanisms, such as the extension of thickened crust.

The main conclusions from the application of the modelling is that for highly extended margins and basin structures the observed basin depth can only be attained when the total magnitude of crustal thinning is constrained from crustal thickness changes rather than by fault-displacement measurements. Nevertheless, reconstruction of the seismically visible faults simulates a comparable basement topography to that observed. Consequently, while it may be regarded that upper crustal faults account for the apparent magnitude of extension at the level of the basement, processes occurring deeper in the crust and mantle may thin the crust without appreciably deforming the faulted basement topography. Processes such as lower crustal flow, penetrative pure shear, lateral flow of weak ductile crustal layers between stronger layers, and a component of subseismic scale deformation may combine to produce whole crustal thinning without significant mismatches in upper and lower crustal stretching factors. Clearly, these processes require further investigation both through modelling and observation.

Appendix: InterMARGINS Extensional Deformation of the Lithosphere (IMEDL) benchmarking exercise: application of a kinematic modelling approach to the Iberian margin

Introduction

In this section the 2D kinematic modelling approach described in the section on 'integrated kinematic modeling of lithosphere extension and compression' in the main part of the paper has been applied to the Iberian margin as part of a benchmarking exercise carried out for the 2004 InterMARGINS Extensional Deformation of the Lithosphere (IMEDL) workshop. The aim of this benchmarking exercise was to establish the strengths and weaknesses of different modelling approaches (i.e. dynamic, kinematic, inverse, etc.) when applied to the same case study consisting of a combined section across the Iberia and Newfoundland margins, including their respective ocean–continent transitions. The database made available for the exercise consisted of multichannel seismic reflection data, refraction data, published material and Ocean Drilling Program (ODP) drilling data sets. Our main aim, as part of this benchmarking exercise, was to show how a kinematic modelling approach can be applied to provide insights into the geological and geodynamic processes that control overall subsidence history and basin architecture of a passive margin setting.

Data constraints

The modelling carried out has focused on the Iberia margin and is mainly based on a regional seismic reflection line, Iberia Seismic Experiment – 1 (ISE-1), which was made available for the IMEDL benchmarking exercise. The geological evolution of the Iberian margin is described in a number of publications (e.g. Pinheiro *et al.* 1996; Whitmarsh *et al.* 1996) and will not be repeated here. Seismic line ISE-1, which was acquired in 1997, is shown in Figure A1a. It starts about 11 km to the west of the Portuguese–Spanish coastline, crossing the Galicia Interior Basin, the Galicia Bank, the deep Galicia Basin and the Peridotite Ridge. The section has been interpreted to show the sea bed, top basement and crustal faults (Fig. A1b).

In order to start building the first model, the magnitude of heave has been quantified for each of the faults that have been identified (Fig. A1c). The heave along each fault has been measured as the distance from the footwall cut-off to the point of contact between basement and the fault. No attempt has been made to reconstruct the footwall tops to take into account material lost through erosion so it is acknowledged that the heave values measured are likely to be an underestimate. Total extension, as given by the sum of all heave values, is 104.5 km, which approximates to about 50% extension ($\beta = 1.5$).

Application of kinematic modelling

One of the main observations to arise from the modelling of the Black Sea basin in the main part of the paper is that it is not possible to use the observed magnitude of faulting to constrain deformation throughout the lithosphere. This is partly because the data acquisition and interpretation process does not reveal all of the faults that exist at a variety of scales within the crust. However, there is a dilemma in that many basins within the geological record show a mismatch between the deformation due to faulting and overall thinning of the crust that is too great to explain by a lack of identification of faults within the available data. This mismatch is apparent across the Iberian margin where the β value determined from the fault heave values is about 1.5, which leads to post-extensional crustal thickness of about 23 km. In contrast, seismic refraction data (Whitmarsh *et al.* 1996) indicate that the crust is about 2–4 km thick at the western edge of the section, which is indicative of β values of 8 or 9. One possible scenario that can reconcile the observed low magnitude of fault deformation with high attenuation

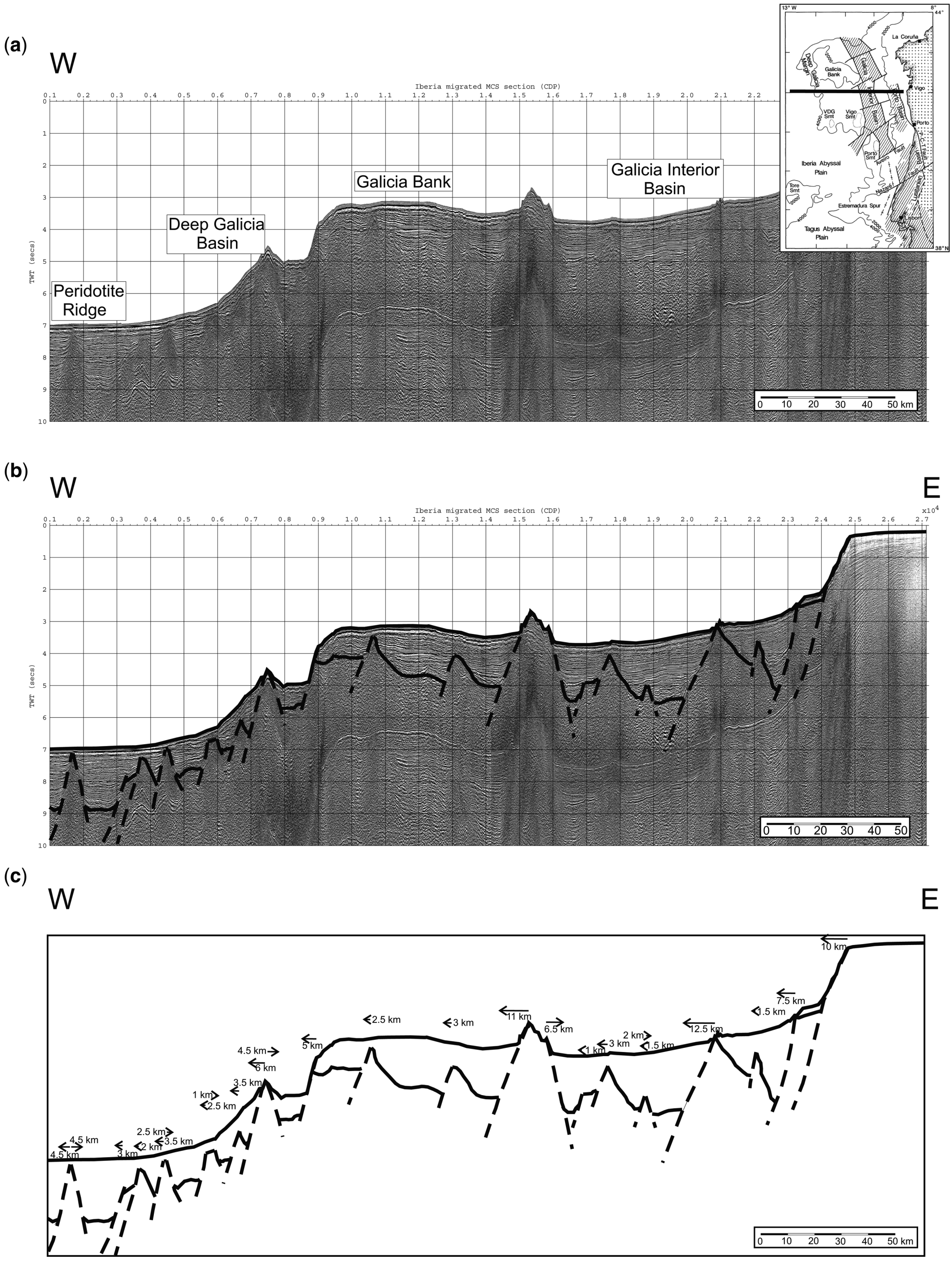

Fig. A1. (**a**) Iberia Seismic Experiment – 1 (ISE-1) regional seismic reflection line that was made available for the 2004 IMEDL benchmarking exercise. The *x*-scale is defined in CDP locations, which are 12.5 m apart, giving the section a total length of about 325 km. (**b**) The section has been interpreted to show the sea bed, top basement and crustal faults. (**c**) The magnitude of heave has been measured for each of the faults that have been identified.

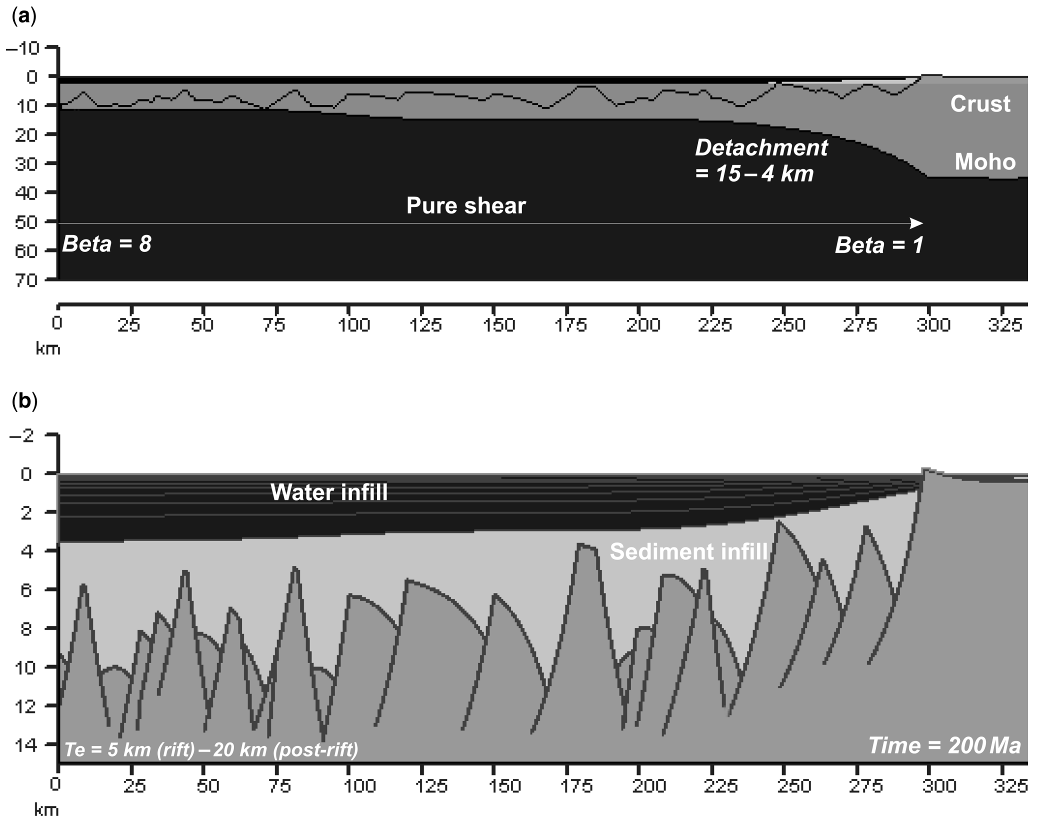

Fig. A2. Model based on reflection line ISE-1 assuming a migrating detachment depth (4–15 km). It shows a realistic basement geometry and overall pattern of relative uplift and subsidence across the margin.

of the crust determined from geophysical data is a migrating detachment or necking depth (Braun & Beaumont 1989). This depth determines the relative importance of upper crustal thinning due to faulting relative to lower crustal thinning due to a more regionally distributed process. It is possible therefore that during the evolution of the Iberian margin there has been a change from a deep detachment depth and therefore dominance of crustal thinning due to faulting to a shallow crustal necking depth where there is a dominance of lower crustal thinning. The driving mechanism for this migration of the detachment depth can be explained by an increase in the geothermal gradient as the rifted margin evolves (e.g. Spadini *et al.* 1996).

Figure A2 shows a model profile based on a migrating detachment depth. The deformation due to faulting is based on that interpreted from the ISE-1 section (Fig. A1b, c) and assuming a fault detachment depth of 15 km, which is compatible with evidence from deep seismic reflection data (e.g. Hall *et al.* 1984), seismological investigations (e.g. Jackson & McKenzie 1983) and rheological modelling of the lithosphere (e.g. Kusznir & Park 1987). The crust is assumed to have a predeformational thickness of 35 km (Pinheiro *et al.* 1996; Manatschal 2004). A second phase of extension is then modelled with the necking depth positioned at a depth of 4 km, and the lower crust and mantle lithosphere is gradually thinned from no deformation in the east to a maximum *B* value of 8 at the western edge of the section in order to reproduce the observed attenuation of the crust. The model has been allowed to run for a simulated time of 200 million years to represent the first phase of rifting in the lower Jurassic. For simplicity, the basin has been assumed to fill to sea level with sediment during rifting, whereas the post-rift phase has been water filled to avoid overloading and overdeepening the basement. The elastic thickness of the lithosphere is taken to be 5 km at rifting, which is compatible with a number of active rift settings (e.g. Barton & Wood 1984; Kusznir *et al.* 1991; Van Wees & Cloetingh 1996) gradually rising to 20 km at the end of the model evolution in response to cooling of the lithosphere. The model shows distinct uplift of the footwall blocks covered by a broad blanket of thermal subsidence.

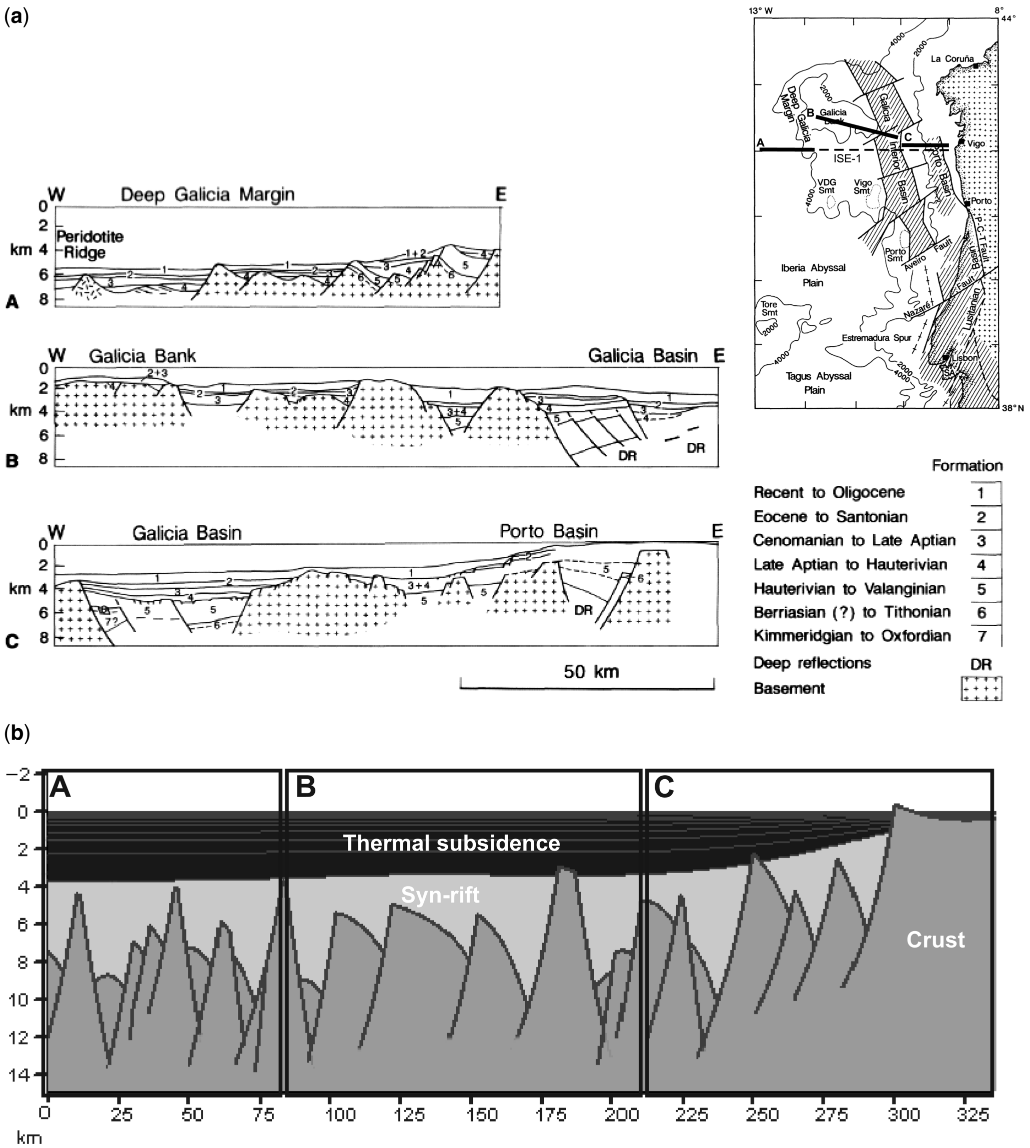

Fig. A3. (**a**) Composite section across the Iberian margin showing structure and stratigraphy with respect to depth (adapted from Pinheiro *et al.* 1996). The location map shows the near proximity of this section to seismic line ISE-1. (**b**) Modified model (cf. Fig. A2) whereby any subsided part of the basin following rifting has been half-filled with sediment and allowed to subside flexurally. Any remaining subsidence is filled with water. This model shows a close comparison to the structural and stratigraphic cross-section presented in Figure A3a.

The resultant model profile exhibits both a realistic basement geometry and overall pattern of subsidence across the margin. A published section across the Iberian margin by Pinheiro *et al.* (1996) has been used to make a detailed comparison with the model results (Fig. A3a). This section shows the variation of structural and stratigraphic components with respect to depth and has some overlap with seismic line ISE-1. A comparison between the western parts of this section and the model profile in Figure A2 shows that the modelled basement depth is reasonably accurate with the tops of the fault blocks at depths of 4–5 km and basement within the graben structures at depths of 6–8 km. However, there are mismatches between the model results and interpretation. In particular, the modelled water depth is too low and the sediment thickness is too great. This incompatibility can be reduced by decreasing the amount of infill of the basin. A new model has been generated in Figure A3b using an identical set of parameters to that shown in Figure A2, except that any basin subsidence generated immediately following rifting has been half-filled with sediment, while any remaining component flexural subsidence has been filled with water. Although the modified model shows a close match to the western part of the section, the Galicia Bank region is too deep in the model. This mismatch can be explained by an overestimation of the magnitude of fault-controlled extension in the region. Alternatively, a closer match could also be obtained by modifying the flexural strength of the lithosphere. The eastern part of the model shows a reasonably accurate geometry and depth profile across the fault blocks, apart from the exaggerated footwall uplift structure at the edge of the profile. This feature is not present in the geological section possibly owing to either erosion or by additional extension off-section to the east.

Summary

A kinematic model of lithosphere extension has been included within a benchmarking exercise to compare the strengths and weakness of different modelling methods in the context of the Iberia margin. Twenty four crustal faults have been interpreted in seismic section ISE-1 across the Iberia margin, exhibiting a total horizontal extension of about 105 km ($\beta = 1.5$). This magnitude of fault-controlled deformation has to be reconciled with the overall attenuation of the crust to generate a realistic magnitude of subsidence, which can be explained by a gradually shallowing necking depth.

We would like to thank BP and TPAO for providing data for this study. S. Egan is also grateful for the opportunity to have taken part in the 2004 IMEDL workshop. The authors would also like to thank N. Christie-Blick, A. Goodliffe and an anonymous reviewer for their constructive comments during the review process of this manuscript.

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