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The formation of the south-eastern part of the Dniepr–Donets Basin: 2-D forward and reverse modelling taking into account post-rift redeposition of syn-rift salt

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Abstract

Forward and reverse modelling of structure and stratigraphy has been used to investigate the syn-rift (Late Devonian) and early post-rift (Carboniferous) evolution of the south-eastern part of the Dniepr–Donets Basin (DDB). Modelling was carried out with and without taking into consideration the withdrawal and surface extrusion of Devonian salt during the formation of salt diapirs. The great thickness of Carboniferous deposits can be explained by the superimposed actions of three processes: post-rift thermal subsidence, withdrawal of Devonian salt from the mother layer during phases of salt diapir activity, and regional subsidence of the East European Platform. The effects of other tectonic and/or non-tectonic processes are not required.

Forward syn-rift modelling using the flexural cantilever model of sedimentary basin formation predicts the total syn-rift extension across the south-eastern DDB to be approximately 65 km with a maximum β stretching factor of 2.4. Shallowing of the Moho during the syn-rift phase is estimated to be 15 km. The present-day Moho, after thermal subsidence and basin fill, is predicted to be 4–6 km shallower than surrounding regions.

In the axial zone of the south-eastern DDB the thickness of the Devonian syn-rift sequence may have reached 7.5 km by the end of the rift stage. This is 3–3.5 km more than at present. The thickness reduction is due to the outflow of Devonian salt during post-rift periods of halokinetic activity in the early Visean, the middle Serpukhovian, and in the Early Permian. The withdrawal of salt from the mother layer produced additional accommodation space and up to 1.5–1.7 km of the total eventual thickness of the Carboniferous sedimentary succession can be explained as a result of this.

Keywords: Dniepr–Donets Basin; Salt tectonics; Subsidence modelling; Rift basin

1. Introduction

The Ukrainian Dniepr–Donets Basin (DDB) is located in the south-eastern part of the East European Craton along a NW–SE trending axis between the present-day Ukrainian Shield and Voronezh Mas-

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sif (Fig. 1). It is part of the same rift basin system as the shallower Pripyat Trough to the north-west (mainly in Belarus) and the inverted Donbas Basin (Foldbelt) and its south-eastward extension to the south-east (straddling the Ukraine–Russia border). The Upper Devonian syn-rift sequence, which was deposited in a shallow-marine environment and contains significant quantities of salt, is overlain by a thick post-rift sequence of Carboniferous age and younger (Chirvinskaya and Sollogub, 1980; Gavrish, 1989; Chekunov et al., 1992; Stovba et al., 1995, 1996). With the exception of a widespread unconformity developed in the Permian, when at least part of the basin was uplifted and eroded (Stovba et al., 1996), the DDB contains a nearly complete stratigraphic record of basin forming processes.

The north-western part of the DDB is tectonically "well-behaved". First-order tectonic processes of basin origin and evolution—rifting and its thermomechanical effects on continental lithosphere, as revealed by subsurface geology (basin stratigraphy and fault architecture) and by geophysical studies (crustal structure from seismic, geopotential and geothermal data)—are simultaneously explicable in a framework similar to that of most other intracratonic rifts and passive continental margins (cf. van Wees et al., 1996; Kusznir et al., 1996). The integration of basin infill with what is known of crustal structure

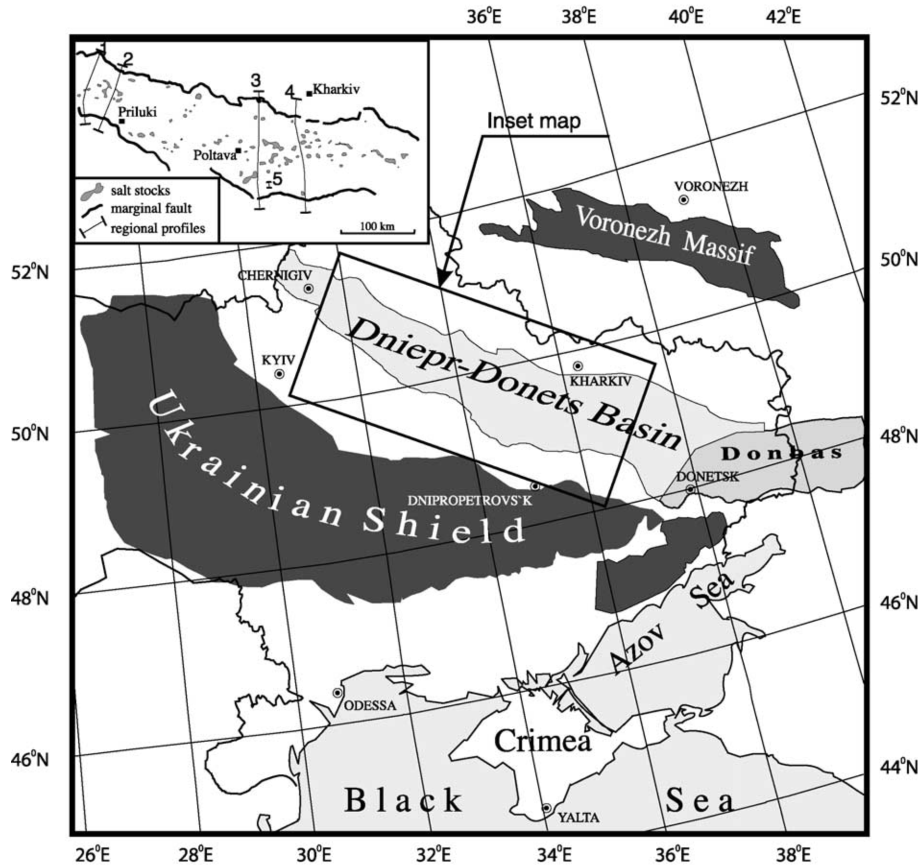


Fig. 1. Tectonic map of the south-eastern part of the Eastern European Platform, with light shading indicating the central rift of the DDB and the inset map showing the locations of the two crossing profiles studied in this paper (Profiles 3 and 4). The two profiles studied by Kusznir et al. (1996) are Profiles 1 and 2.

becomes increasingly problematic when passing from the north-western part of the DDB to its south-eastern one and thence to the Donbas Foldbelt (van Wees et al., 1996; Stovba and Stephenson, 1999; Stephenson et al., 2001). The enigmatic post-rift evolution of the south-eastern part of the DDB is highlighted by an excessively thick post-rift Carboniferous sedimentary succession (up to 11 km thickness) compared to the degree of tectonic activity recorded in the stratigraphy and basin architecture. No basin evolution model based solely on a post-rift thermo-mechanical subsidence mechanism can satisfactorily explain the thickness of the post-rift strata in that part of the DDB (cf. van Wees et al., 1996). Kusznir et al. (1996) deduced, from unconformities related to footwall uplift on the rift-bounding fault systems, that approximately 300 m of regional uplift occurred during the rifting phase in the north-west DDB. Subsequently, the same 300 m would be recovered, according to the modelling, as a regional downwarping during the post-rift stage in order to provide sufficient accommodation space in the Carboniferous. These authors suggested that the inferred transient regional vertical crustal motions were generated by the dynamic (i.e., not thermal) effects of a mantle plume. Although this fits well for the north-west DDB, application of the same general mechanism to basin development further south-east is problematic. There, as demonstrated by van Wees et al. (1996), greater and greater amounts of Carboniferous accommodation space are required to model satisfactorily the post-rift stratigraphy. However, there is no evidence for syn-rift regional uplift increasing to the south-east.

Structural reactivation, including inversion and salt tectonics, have played an important role in forming the present-day basin architecture. Major post-rift structural reactivation took place at the beginning of the late Visean and in the middle of Serpukhovian, in the Early Permian, and between the Mesozoic and Cenozoic (Stovba et al., 1996; Stovba and Stephenson, 1999). Within the north-western part of the basin, the Carboniferous reactivations and salt diapirism were only of minor significance, which greatly simplifies basin modelling investigations. Carboniferous and Early Permian structural reactivations occur mainly in the south-eastern part of the DDB. van Wees et al. (1996) considered the Late Devonian syn-rift phase as well as post-rift reactivation phases in modelling the observed subsidence data. Carboniferous post-rift subsidence could be explained satisfactorily by the superposition of a Visean rift-induced thermal anomaly onto the one derived from Late Devonian rifting. The preferred model was one that incorporated an inhomogeneous lithosphere thinning with two independent "stretching" factors, for the crust and sub-crustal lithosphere. These were in the ranges 1.0–1.51 and 1.01–10, respectively, increasing from north-west to south-east.

One non-tectonic mechanism that could have led to the additional accumulation of Carboniferous and younger sediments and to a post-depositional decrease of the total thickness of the Devonian syn-rift sequence is the withdrawal of Devonian salt during the post-rift evolution of the south-eastern part of the DDB. van Wees et al. (1996) schematically described the effects of such a mechanism. The aim of this study is to consider, through quantitative basin modelling, the development of the south-eastern part of the DDB during its Palaeozoic syn-rift and post-rift stages, incorporating the influence of salt diapirism on forming the present day basin structure. In particular, this study aims to examine: (1) syn-rift and post-rift subsidence and its relationship with the withdrawal of Devonian salt from the mother layer during Palaeozoic phases of salt tectonics, (2) syn-rift uplift and the subsequent erosion responsible for the exhumation of the Ukrainian Shield and Voronezh Massif, and (3) the relationship between rifting processes and post-rift Moho depth.

Reverse post-rift basin modelling, consisting of flexural backstripping, decompaction and reverse post-rift thermal subsidence modelling (e.g. Roberts et al., 1993; Kusznir et al., 1995; Nadin and Kusznir, 1995), has been applied to stratigraphic cross-sections based on seismic reflection data within the south-eastern part of the DDB in order to determine post-rift subsidence history. The simple process of sequential removal of stratigraphic units, followed by decompaction and flattening to sea level, has also been used to examine burial history.

In addition, forward modelling of the syn-rift and early post-rift development of the DDB has been carried out using the flexural cantilever model of continental extension and rift basin formation (e.g.

Kusznir et al., 1991, 1995; Kusznir and Ziegler, 1992). This allows an estimation of extension across the basin, flank uplift and departures from simple rift-related subsidence. The flexural cantilever model combines a 2-D formulation of the McKenzie (1978) rift basin model with the assumption that upper crustal extension takes place on planar faults with an equal amount of distributed extension in the lower crust and mantle. It is also assumed that all loads generated by crustal thinning, geotherm perturbation and re-equilibration, and sedimentation and erosion are regionally isostatically compensated. Sediment compaction is also included in the model.

2. Review of the geology of the Dniepr–Donets Basin

2.1. Introduction

The DDB formed as a result of Late Devonian intracratonic rifting and comprises pre-rift and syn-rift Devonian sequences, overlain by thick post-rift Carboniferous, Permian, Mesozoic, and younger sediments (Fig. 2). Within the rift, Devonian sediments overlie crystalline basement, while on the rift shoulders Devonian strata are generally absent with Carboniferous units unconformably overlying basement.

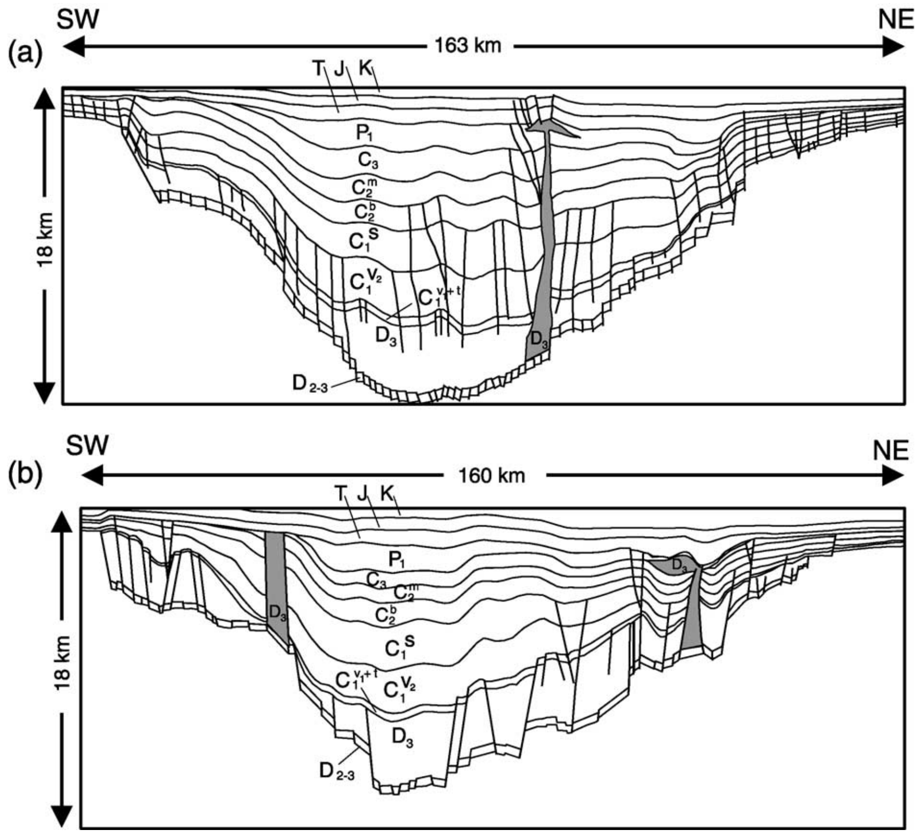


Fig. 2. Interpreted and depth-converted regional seismic cross-sections through the DDB (a) Profile 4 and (b) Profile 3, showing the regional blanket of Carboniferous–Recent sediments lying above the Devonian, the thickness of which is fault-controlled. Stratigraphic key for this and ensuing figures: D_{2-3} = Middle–Upper Devonian; C = Carboniferous; C_1 = Lower Carboniferous, t—Tournaisian, v_1—lower Visean, v_2—upper Visean, s—Serpukhovian; C_2 = Middle Carboniferous (Ukrainian/Russian usage—e.g. Bashkirian and Moscovian), b—Bashkirian, m—Moscovian; C_3 = Upper Carboniferous (Ukrainian/Russian usage—e.g. Kasimovian and Gzelian); P_1 = Lower Permian, T = Triassic; J = Jurassic; K = Cretaceous; Mz = Mesozoic.

Maximum sediment thickness, accumulated during Late Palaeozoic and Mesozoic times, ranges from 2–6 km in the north-west to 15–19 km in the south-east (Stovba et al., 1996; Stovba and Stephenson, 1999). Over its entire extent the rift basement is broken into blocks of various sizes by disruptive faults with offsets in the range 100–2000 m forming characteristic large, rotational fault blocks and half grabens, bounded by basin-parallel to normal marginal faults, or by major horst blocks. The thickness of the Devonian succession displays significant variation, often over very short distances, and reaches a maximum of about 4 km (Fig. 2).

2.2. Devonian pre-rift and syn-rift history

Pre-rift Devonian sedimentation in the DDB, commencing in the Middle Devonian (~ 383 Ma), took place in a shallow sea and subsidence was characterised by a large regional sag without any substantial differential vertical movements of basement blocks. Between late Frasnian (370 Ma) and the end of the Devonian (363 Ma) the main stage of rifting took place. The Late Devonian stage of development was of typical rift type with high and laterally variable rates of downwarping, formation of grabens and half-grabens within the basin, and uplift and erosion of the rift shoulders, especially on the southern side of the rift. Faulting fractured the crystalline basement into small-scale blocks of dimensions 2–5 km and less. Major depocentres, separated by uplifted blocks, formed during this time (Stovba et al., 1996). The pre-rift sediments, which appear to have been deposited in a platformal environment, were presumably eroded on the rift shoulders and on some of the larger intrabasinal highs during the syn-rift stage.

The lowermost Devonian syn-rift sediments are represented by a salt series with a thickness locally reaching 1000 m and more. The salt alternates laterally with clastic–carbonate rocks. It most commonly occurs in the Frasnian where it is called the "lower salt". The "upper salt", of Famennian age, is less widespread in the DDB, occurring only in the north-western part of the basin. The evaporitic rocks of the "lower salt" were modified by diapirism during the post-rift stage of basin development and now include numerous bodies with lens-, ridge-, and stock-like geometries intruding overlaying layers. Salt stocks may be up to 15 km high (Fig. 2).

Due to active rift processes, the basin stratigraphy records frequent transgressions and regressions at regional and local scales. Frequent changes in paleogeographic environments, both in space and time, are evident and the Famennian succession, consequently, contains interbedded clastic and carbonate rocks, together with effusives, pyroclastic rocks and salt. Along the southern margin of the basin, immediately adjacent to the rift margin fault, the amount of clastic material increases; it comprises unsorted and irregular material frequently containing large blocks of crystalline rock displaying no evidence of weathering (Eisenverg, 1988). These large clasts are similar in composition to Archean and Proterozoic basement strata occurring on the southern shoulder of the basin. Similar units, but of smaller thickness and better sorted, are observed in some areas along the northern marginal faults. Coarse-grained rocks give way laterally to more fine-grained rocks towards the axial part of the basin.

2.3. Post-rift history

While Devonian sediments are usually absent on the flanking shoulders of the rift basin and also on some of the intrabasinal highs, Tournaisian and lower Visean sediments are present as a nearly continuous blanket and lie unconformably upon eroded Devonian sediments and crystalline basement on the intrabasinal highs. Tournaisian–early Visean sediments comprise shallow-water and, in places, continental deposits (Eisenverg, 1988). Very shallow to zero bathymetry at the end of the Devonian is indicated by a widespread unconformity developed then; shallow water deposition prevailed through the Early Carboniferous (Dvorjanin et al., 1996). The relatively thin stratigraphic units of Tournaisian and lower Visean age are interpreted as representing the earliest part of the post-rift fill of the basin. The main rifting stage is therefore assumed to have terminated in late Famennian (ca. 363 Ma).

Above the Tournaisian–lower Visean is a very thick, finely layered clay–sandstone succession which continues into the Upper Carboniferous. The depositional environment was shallow marine with occasional lagoonal and terrestrial conditions (Dvorjanin et al., 1996; Izart et al., 1996, 1998). A succession of sediments with different compositions and facies were laid down in a general background of basin subsidence with some influence of wave activity. In general, the Carboniferous and younger post-rift sedimentary basin of the DDB has the configuration of a broad syncline centred on the rift axis (Fig. 2), overlapping the rift shoulders, and increasing in thickness depth towards the south-east. Carboniferous sediments reach a thickness of 11 km, with a maximum depth of their base at about 15 km (Stovba et al., 1995, 1996; Stovba and Stephenson, 1999).

During the Late Carboniferous the depositional environment of the basin changed. The lateral extent of the basin became smaller and shallow-marine deposition gave way to continental and lagoonal sedimentation, leading to evaporitic conditions in the Early Permian (Korenevskiy et al., 1968). In the southern pre-shoulder zone of the DDB the Lower Permian sequence abruptly decreases in thickness and pinches out as a result of a decrease in depositional thickness as well as subsequent erosion (Fig. 2). In contrast, its thickness decrease towards the northern shoulder of the basin is far more gradual.

Sedimentation resumed in the Triassic, a time of tectonic quiescence, rising sea levels, and the resumption or continuation of post-rift subsidence. Mesozoic strata unconformably overlie the Palaeozoic series and consist of marine and continental sediments. The Upper Cretaceous succession consists mainly of marl and chalk. The Cenozoic succession includes clastic sediments, mainly sandy rocks, marls, sandstones and shales, reaching a maximum thickness of 300–400 m (Eisenverg, 1988).

The DDB was affected during its Permian–Carboniferous evolution by discrete pulses of post-rift extensional deformation tectonic in origin: namely, at the end of the early Visean, during the middle Serpukhovian, and during latest Carboniferous–earliest Early Permian times (Stovba et al., 1996). Structural reactivation at the end of the Cretaceous is compressional in nature (Stovba and Stephenson, 1999; Saintot et al., 1999). These events increased in intensity towards the south-east, being minor to not observed in the north-western part of the basin.

3. Salt tectonics in the Dniepr–Donets Basin

Salt structures in the DDB formed episodically. Salt flow began as early as during the deposition of the Devonian syn-rift sediments that directly overlie the Frasnian salt series (cf. Chirvinskaya and Sollogub, 1980; Stovba et al., 1996). Primary salt structures formed during the rift stage and influenced the location of many younger salt pillows and diapirs. The onset of the main post-rift phases of salt movement is intimately related to periods that also display active regional tectonics (Stovba, 1998; Stovba and Stephenson, 1999). In particular, the various onsets of salt movements correspond with periods of extensional structural reactivation in the late Visean, the middle Serpukhovian, and the Early Permian. However, the duration of periods of active halokinesis, especially when salt became extrusive, exceeded the duration of regional tectonic activation. Periods of active halokinesis were followed by periods of quiescence during which up to several kilometres of sediments could be deposited before new regional tectonic forces would trigger renewed salt movement (cf. Stovba and Stephenson, in press).

Salt flow into salt structures created additional space for sediment accumulation adjacent to the structures themselves. Fig. 3 shows a salt structure that formed episodically in the late Visean, the middle Serpukhovian, and the Early Permian. The growth of this salt structure was accompanied by the development of a rim-syncline. A significant proportion of the upper Visean sediments (up to one-third in the north and up to one-half to the south of the structure) was accumulated within this primary rim-syncline. The subsidence that provided the accommodation space for these Visean sediments can be seen to have been produced by the outflow of Frasnian salt from the salt series itself into the core of the salt anticline. The thinning of the Tournaisian–lower Visean succession towards the top of structure is related to erosion in the earliest late Visean, simultaneously with the formation of the rim-syncline. The late Visean growth phase was followed by a period of quiescence prior to renewed uplift after the deposition of the lower Serpukhovian. The period of quiescence also preceded the renewal of salt flow at the end of the Palaeozoic.

Salt tectonics led also to the formation of major salt diapirs that were channels for outflow of Devonian salt

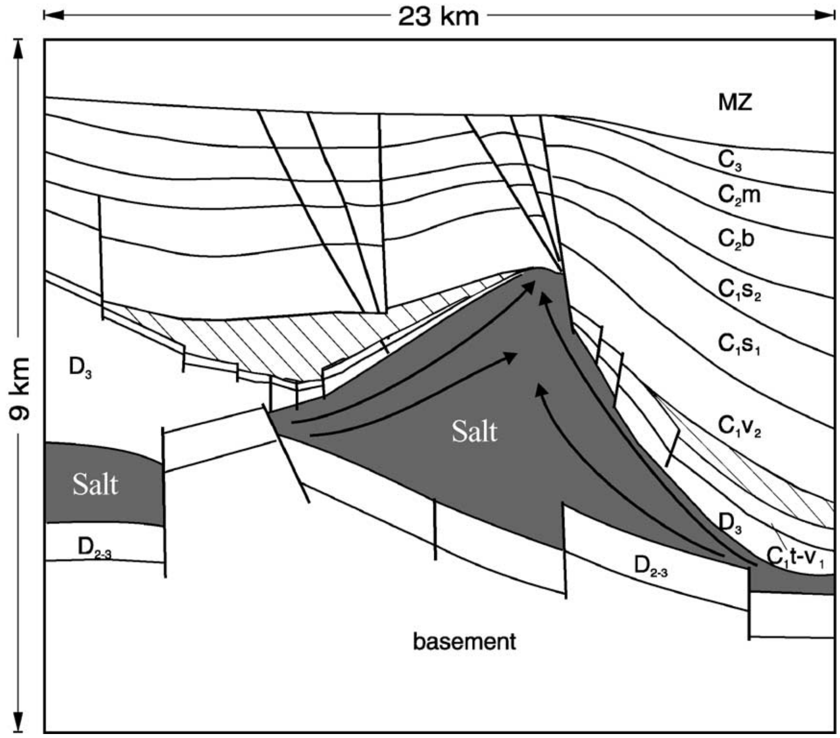


Fig. 3. Depth converted seismic section showing a salt anticline that formed during three stages of tectonic reactivation in the DDB. The formation of this salt structure was accompanied by the development of rim-synclines. The cross-hatched part of the upper Visean was deposited during outflow of Devonian salt beneath the primary rim-syncline towards the core of the salt structure.

onto the depositional surface. In the axial zone of the south-eastern DDB, i.e. in the zone where a huge thickness of Carboniferous sediments have been accumulated, there are two principal lines along which mushroom-like salt diapirs are found (Fig. 1). These exhibit a close spatial relationship with the locus of extremely high stretching values determined with 1-D modelling by van Wees et al. (1996). Diapirism along these trends occurred primarily during periods of regional tectonic reactivation, as mentioned above (Stovba et al., 1996; Stovba, 1998). Secondary rim-synclines developed around them during salt outflow, thereby producing additional accommodation space for upper Visean, Serpukhovian, and Lower Permian sediments in the axial zone of the DDB. The whole axial zone of the south-eastern DDB may actually be considered as a secondary rim-syncline as regards to salt diapirs (Stovba and Maystrenko, 2000a,b). The withdrawal of the Devonian salt through the stems of salt diapirs led also to a reduction in the total thickness of the Devonian syn-rift sequence as preserved today.

In post-Permian time the main period of active salt movement was during the latest Cretaceous–earliest Paleogene—the time of a regional compressional event that affected the DDB (Stovba and Stephenson, 1999; Saintot et al., 1999). Devonian salt intruded existing salt domes at this time promoting the growth of large anticlines over Early Permian diapirs (Chirvinskaya and Sollogub, 1980; Gavrish, 1989), as seen in Fig. 2. In areas where Lower Permian salt was absent, some Early Permian diapirs pierced the Mesozoic overburden during this compressional event (Chirvinskaya and Sollogub, 1980).

It may be surmised from the observations described above that neglecting salt tectonic processes can cause significant errors in the quantitative 1-D and/or 2-D modelling of tectonic subsidence in the

DDB. Specifically, overlooking the role of salt movements could lead to an understatement of the magnitude of tectonic subsidence and the degree and rate of basin extension during the syn-rift stage and a concomitant overestimation of the magnitude of tectonic subsidence during the post-rift stage. To take into account the influence of the salt withdrawal in a tectonic modelling study it is necessary to establish the thickness of the autochthonous salt that was extracted from its original depositional position onto paleo-surfaces during periods of active salt tectonics. At present there are no distinct quantitative criteria available with which to make such an evaluation. However, an approximate value can be inferred from the geological data.

The accumulation of sediments in the south-east DDB in an environment of moderately rapid tectonic subsidence continued uninterruptedly until the Early Permian. At that time there was an extensional or transtensional tectonic event followed by uplift of much of the DDB—excluding the axial zone (Stovba and Stephenson, 1999). The subsidence/uplift of the axial zone of the DDB in the Early Permian can be assumed to be a combination of (1) residual thermal subsidence following Late Devonian rifting and Carboniferous extensional reactivations, (2) relative sea level fall and/or regional uplift that affected the whole East European Platform, (3) tectonic uplift of the southern margin of the DDB, and (4) the withdrawal of Devonian salt onto the paleo-surface. The relative contributions of the various processes are difficult to calculate. However, geological data indicate that salt stock locations correspond to areas where Lower Permian evaporites are thickest. Also, most diapirs formed during the accumulation of evaporite sediments due to passive piercing (salt extruded onto the paleo-surface at that time). Thus, it can be assumed that Lower Permian sediments accumulated mainly due to the withdrawal of the Devonian salt. This could lead to an overestimation of salt withdrawal effects. On the other hand, some of the Early Permian extruded salt may have been dissolved or eroded during basin uplift and/or sea level fall and, thus, the original thickness of the Lower Permian sediments in the basin axial zone could be more than what is observed now.

The volume of autochthonous salt that was lost from the Devonian mother layer during the late Visean and Serpukhovian phases of salt diapir formation can only be evaluated even more poorly than for the Early Permian phase. Nevertheless, geological data reveal that significant additional sediment accommodation space was created during these stages (cf. Fig. 2). In order to ensure that the influence of the Early Carboniferous salt movements are not overestimated it is assumed that during each of the two Carboniferous phases the rate of salt withdrawal was half of that inferred for the Early Permian event. The area of active salt withdrawal was assumed to be the same for all three phases. This assumption is supported by geological observations on the recurrence of salt diapir formation in the axial zone of the DDB (Stovba, 1998).

4. 2-D forward and reverse modelling

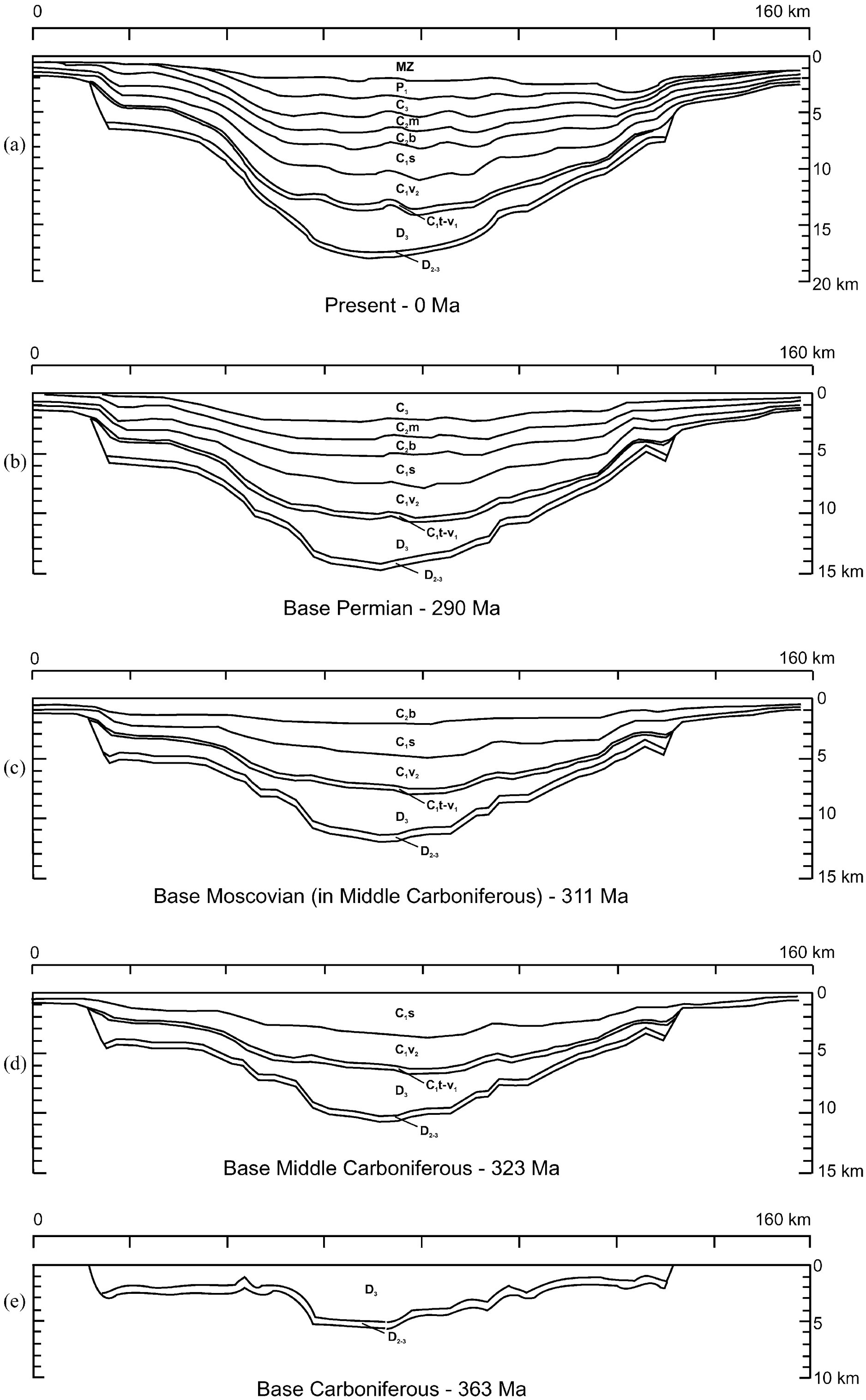
4.1. Introduction

2-D forward and reverse modelling of the tectonic evolution the south-eastern part of the DDB has been carried out using data from two stratigraphic cross-sections based on seismic reflection data (Fig. 2). These are referred to as Profiles 3 and 4 (cf. Kusznir et al., 1996 for Profiles 1 and 2) and are located in Fig. 1 (inset). Two modelling scenarios have been investigated: a conventional one that does not take into consideration the withdrawal of Devonian salt during post-rift basin evolution and one that does. Modelling results are shown in detail for Profile 4 while for Profile 3 only the final, preferred fit between observed data and modelling results is presented.

4.2. 2-D reverse post-rift modelling

A simple approach to analysing post-rift subsidence, where post-rift paleobathymetry is approximately zero, is to remove sequentially the post-rift stratigraphy layer

Fig. 4. Reconstructed cross-section along Profile 4 across the DDB, generated by sequential flattening and decompaction, and showing basin development from the end of Devonian rifting (e) to the present (a).


(a)
0
160 km
MZ
P_1
C_3
C_2m
C_2b
C_1s
C_1v_2
$C_1t\text{-}v_1$
D_3
$D_{2\text{-}3}$
0
5
10
15
20 km
Present - 0 Ma
(b)
0
160 km
C_3
C_2m
C_2b
C_1s
C_1v_2
$C_1t\text{-}v_1$
D_3
$D_{2\text{-}3}$
0
5
10
15 km
Base Permian - 290 Ma
(c)
0
160 km
C_2b
C_1s
C_1v_2
$C_1t\text{-}v_1$
D_3
$D_{2\text{-}3}$
0
5
10
15 km
Base Moscovian (in Middle Carboniferous) - 311 Ma
(d)
0
160 km
C_1s
C_1v_2
$C_1t\text{-}v_1$
D_3
$D_{2\text{-}3}$
0
5
10
15 km
Base Middle Carboniferous - 323 Ma
(e)
0
160 km
D_3
$D_{2\text{-}3}$
0
5
10 km
Base Carboniferous - 363 Ma

by layer, setting the paleo-surface to sea level at each restoration stage while allowing for sediment decompaction. This simple technique has been applied to DDB Profile 4; restored post-rift cross-sections for base Permian, base Moscovian (in Middle Carboniferous), base Middle Carboniferous, and base Tournaisian (top Devonian) are shown in Fig. 4. Decompaction has been computed according to the scheme of Sclater and Christie (1980); compaction parameters used for each layer are given in Table 1. The assumption of paleo-bathymetry equal to zero at all stages of computing of the section for the beginning of Early Carboniferous is clearly an over-simplification. However, observed depositional environments indicate that depositional water depths were small during the Carboniferous (Eisenverg, 1988; Dvorjanin et al., 1996) as well as during later post-rift times.

Reverse post-rift modelling (Kusznir et al., 1995), consisting of flexural backstripping, decompaction and reverse thermal subsidence modelling, has also been carried out. In this modelling technique the process of thermal subsidence, sediment infill and isostatic loading, and sediment compaction are tracked backwards in time from an initial stratigraphic section. Results for Profile 4 are shown in Fig. 5. Modelling has been carried out from top Bashkirian (Fig. 4c) to top Devonian, a time period spanning approximately 50 Myr. Flattening to the top Bashkirian has the advantage of removing structural deformations that were induced by Permian and later tectonic events, and especially the erosion of Upper and Middle Carboniferous sediments caused by Early Permian uplift of the basin margins. Flattening, however, neglects potential horizontal displacement components and provides only an approximate restoration of Permian and Mesozoic/Cenozoic deformation. Reverse post-rift modelling uses flexural isostasy to distribute sediment and thermal loads and is therefore dependent on the flexural rigidity used to define the flexural strength of the lithosphere. Here, the value of the flexural rigidity ($T_e = 3$ km) that was obtained by Kusznir et al. (1996) for the north-western DDB (Profiles 1 and 2; Fig. 1 inset) was used. A laterally varying β “stretching” factor (Fig. 5b), derived from forward syn-rift structural and stratigraphic modelling described in next section, was used to model basin stratigraphy in reverse. The β factor reaches a maximum under the basin centre ($\beta = 1.75$) and decreases to unity (i.e., no “stretching”) under the basin flanks.

The results of the reverse post-rift modelling show the basin flanks restored to some 0–300 m below sea level on the southern margin and some 300–700 m on the north (Fig. 5a). In the basin itself, the restored paleobathymetry varies from 1000 to 1700 m. However, observed depositional environments within the basin suggest a much lower paleobathymetry at base Carboniferous, while the observed rift flank stratigraphy suggests that sub-aerial erosion had occurred. Thus, reverse post-rift modelling with a variable β derived from the forward modelling generates excess paleo-bathymetry at base Carboniferous on both flanks as well as within the basin itself. This kind of

Table 1
Ages and decompaction parameters of the south-eastern part of the Dniepr–Donets Basin

Layer number	ϕ_0 (%)	c (1/km)	ρ_m (g/cm^3)	Age of basal horizon (Ma)	Basal horizon
1	59.0	0.451	2.7	245.0	Beg. Triassic
2	41.0	0.376	2.61	290.0	Beg. Permian
3	57.0	0.400	2.69	303.0	Beg. Late Carboniferous
4	56.0	0.388	2.68	311.3	Beg. Moskovian stage (Middle Carboniferous)
5	57.0	0.410	2.69	322.8	Beg. Bashkirian stage (Middle Carboniferous)
6	60.0	0.453	2.7	332.9	Beg. Serpukhovian stage (Early Carboniferous)
7	60.0	0.459	2.7	345.0	Beg. late Visean
8	63.0	0.541	2.71	362.5	Beg. Carboniferous
9	43.0	0.319	2.63	372.0	Beg. late Frasnian (Late Devonian)
10	57.0	0.402	2.68	383.0	Beg. Middle Devonian

Porosity ϕ is assumed to decrease with depth according to $\phi = \phi_0 e^{-cz}$, where ϕ_0 is surface porosity, c is compaction depth constant, and z is depth; ρ_m is matrix density; Beg.—Beginning.

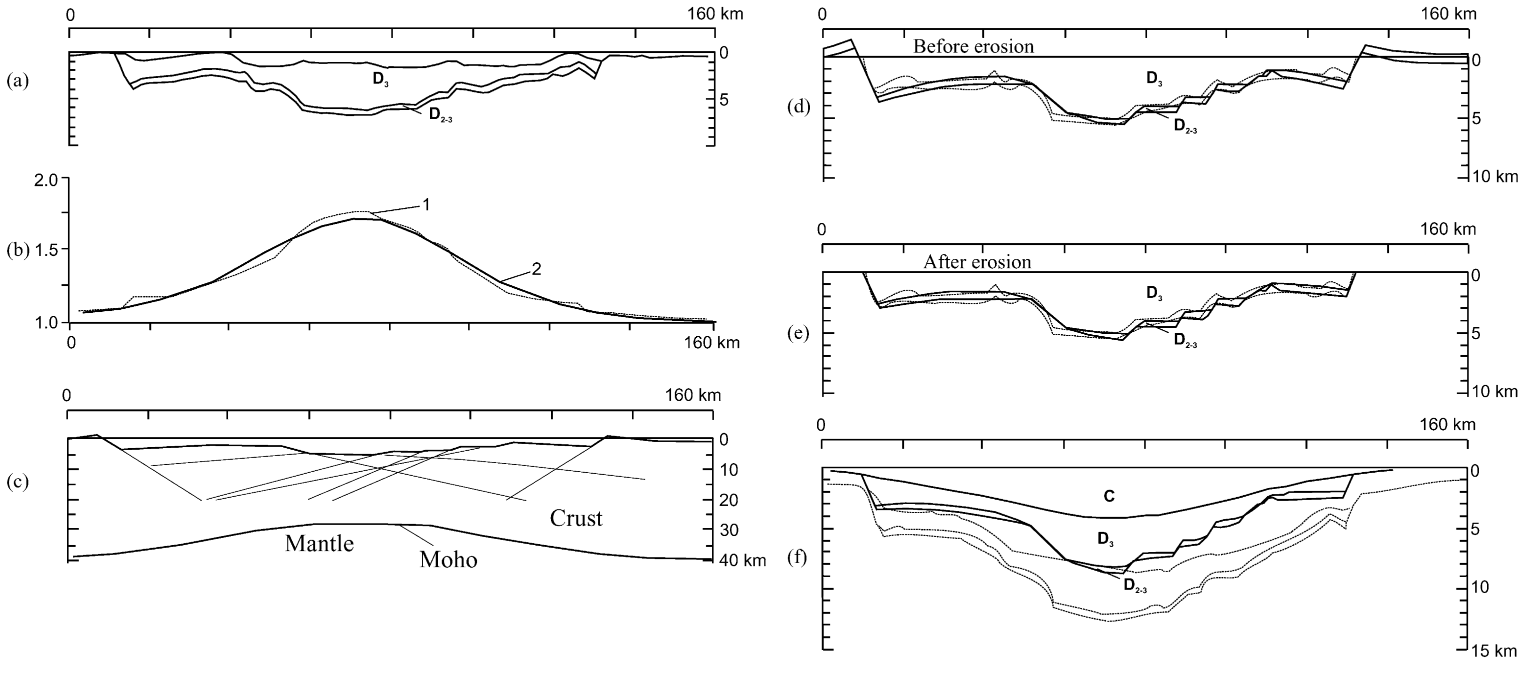


Fig. 5. Results of standard forward and reverse modelling for Profile 4. (a) Reverse post-rift modelling (flexural backstripping, decompaction and reverse post-rift subsidence) using a laterally varying β stretching factor from the preferred-fit forward model. (b) The forward model β stretching factor describing distributed plastic stretching in the lower crust and mantle. (c) Crustal section showing major upper crustal faults, fault-controlled syn-rift basin geometry and Moho uplift underneath the basin in the forward model. (d) Vertically exaggerated section showing basin geometry and footwall uplift on the flanks of the basin before regional erosion in the forward model. Pre-rift sediments are also shown. Observed thicknesses of pre-rift and syn-rift sediments after flattening and decompaction are shown for comparison (dotted line). (e) As for (d) but after erosion to sea-level of all topography, isostatic rebound and further iterative erosion and rebound. Preservation of pre-rift Devonian, and rift basin thickness and geometry are consistent with observations. (f) Forward model of post-rift thermal subsidence to top Bashkirian stage of the Middle Carboniferous following Devonian rifting. The model shows an insufficient thickness of the Carboniferous compared to observations. The thicknesses of observed Devonian and Carboniferous sediments after flattening and decompaction are shown for comparison (dotted lines).

misfit is equivalent in the forward time sense to an additional subsidence during the post-rift stage of the basin evolution. As will be shown in the next section, the reverse post-rift modelling inferences support those of the forward post-rift modelling that additional post-rift subsidence of the basin—not accounted for by the modelling—is required to explain the full thickness of Carboniferous sediments in the axial part of the DDB.

4.3. 2-D forward modelling

Forward modelling is mainly constrained by syn-rift basin geometry and stratigraphy and as a consequence uses a different part of the stratigraphic data set than used by the reverse post-rift modelling described in the previous section.

The flexural cantilever model has been applied to Profile 4 for the syn-rift stage of basin formation (Fig. 5b–f). Observed fault locations and polarities were derived from reflection data and were input into the model and used to predict stratigraphy along the profile to base Carboniferous time, corresponding to the end of the main rift phase. Fault extension was adjusted to provide a preferred fit against the observed basin stratigraphy, which was decompacted and flattened to base Carboniferous. Pre-rift Devonian sediments (D_{2-3}) were included in the model and were given a pre-rift thickness of 0.5 km consistent with that preserved today (and compacted) within the basin centre (cf. Stovba et al., 1996). The calculated syn-rift crustal structure and basin geometry are shown in Fig. 5c. Forward modelled basin stratigraphy, with vertical exaggeration, is shown in Fig. 5d. Syn-rift basin geometry obtained by flattening the observed stratigraphy to base Carboniferous is shown for comparison (dashed lines). The model provides a good fit to observed basin shape and depth for most of the profile. Dips of marginal faults calculated from the modelling are equal to about 45°. This compares with 47–55° from a careful study of geological and seismic data from the south-eastern DDB (Stovba and Maystrenko, 2000a,b), rather close to those obtained from the forward model. In the model, faults with shallow dips were also required within the axial zone of the basin in order to simulate the structural geometry there.

The forward syn-rift model predicts footwall uplift adjacent to the major rift bounding faults and it is assumed in the model that such uplifted areas were eroded during the Late Devonian. The consequences of eroding this footwall uplift, including isostatic-rebound response to erosion, are shown in Fig. 5e. The model provides a good fit to observed syn-rift basin depth and geometry obtained by decompaction and flattening to base Carboniferous and shows complete removal of all Devonian pre-rift sediments on the rift flanks, consistent with geological observations.

The flexural cantilever model was used to model post-rift basin development until the Bashkirian (Middle Carboniferous) for the same profile. Post-rift thermal subsidence is driven by the β profile inferred from the forward syn-rift modelling (Fig. 5b). Sediments are assumed at all stages to fill the basin to sea level. Results, corresponding to 50 Myr of post-rift basin evolution, are shown in Fig. 5f where they are compared with the present-day stratigraphy flattened to top Bashkirian and decompacted. Despite the good fit to observed syn-rift stratigraphy and structure, the forward model fails to produce sufficient post-rift stratigraphy. The misfit between predicted and observed Carboniferous thickness reaches 4.5 km in the basin and 2 km within its flanks. Significant additional regional subsidence is necessary to give a good fit to the observed thickness of Carboniferous strata across the whole basin.

Thus, neither forward nor reverse models have satisfactorily predicted the observed thickness of the post-rift Carboniferous succession. Both suggest that substantial and additional subsidence during the Carboniferous is required to generate sufficient accommodation space for the preserved Carboniferous strata. In the next section, results of forward and reverse modelling taking in consideration salt diapirism in the DDB are presented.

4.4. Reverse and forward modelling taking into consideration salt withdrawal

In view of the characteristics of salt tectonics in the DDB, as discussed in Section 3, some rough estimations of the additional space that could be created by the post-rift withdrawal of Devonian salt have been made for incorporation into the reverse and forward 2-D modelling. Three approaches to this modified modelling experiment have been taken (Fig. 6). The first considers withdrawal of Devonian salt only during the Early Permian (Fig. 6b). The second considers withdrawal of salt during the Early Permian and Serpukhovian (Fig. 6c) and the third considers salt withdrawal in the Early Permian, Serpukhovian, as well as late Visean (Fig. 6d).

In the first scenario, subsidence (and concomitant sediment infill) in the Early Permian is driven by contemporaneous removal of Devonian salt. What are the consequences of this for a model—such as the flexural cantilever model being used here—that is directed at simulating rift-related tectonic subsidence only? In order to ‘‘condition’’ the stratigraphic record for such modelling, a salt layer of thickness equivalent to the thickness of the Lower Permian evaporitic units must be artificially added to the Late Devonian syn-rift sequence. Correspondingly, the Lower Permian sequence must be artificially removed from the observed stratigraphic section (Fig. 6a). In such a way the stratigraphic section shown in

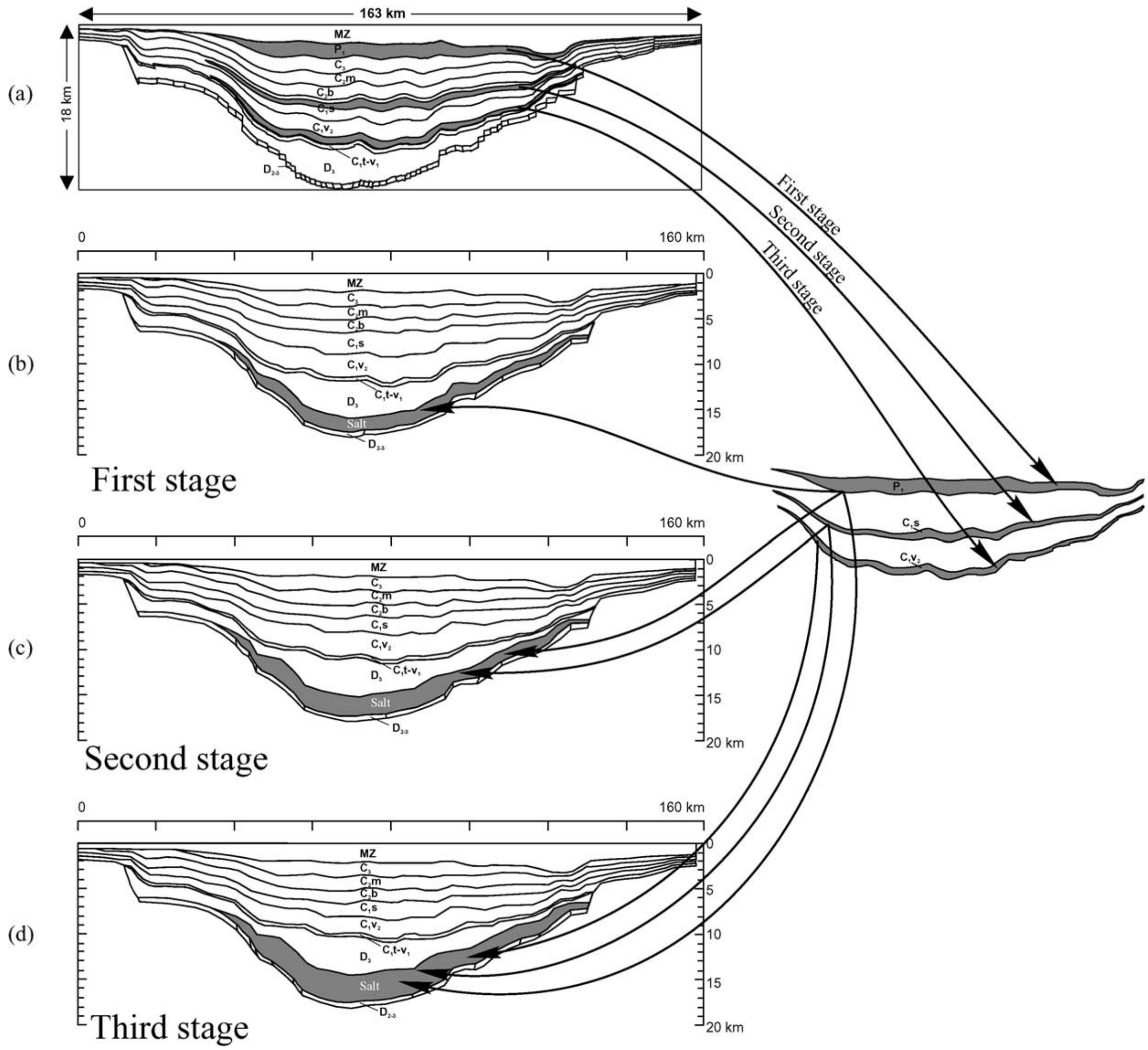


Fig. 6. Basin reconstructions for reverse and forward modelling taking into consideration the withdrawal and redeposition of Devonian salt.

Fig. 6b suggests the "present-day" one that would have been observed in the absence of Early Permian withdrawal of Devonian salt and sedimentation. For the second scenario, in addition to modifying the Lower Permian succession as just described, some of the actual Serpukhovian subsidence—as recorded by the observed Serpukhovian succession—must also be "transferred" to the Late Devonian. The thickness of the intra-Serpukhovian layer that is transferred was arbitrarily taken to be equivalent to half the transferred Lower Permian sequence. The section shown in Fig. 6c thus replicates the fictitious "present-day" situation given the stipulated conditions—that is, without salt withdrawal subsidence effects during the Serpukhovian (partially) and the Early Permian (completely). The third scenario takes this one step further and assumes that some component of the observed late Visean subsidence is also due to contemporaneous removal of Devonian salt. The thickness of the removed salt layer is again arbitrarily taken to be half the Early Permian one. In the third stage, the "observed" section for the second stage has been changed by moving a layer of thickness that is equivalent to half the Lower Permian thickness, from the upper Visean sequence to the Devonian one. The resulting fictitious "present-day" section is shown in Fig. 6d. This represents a model of the DDB as if there had been no salt withdrawal during its Carboniferous–Early Permian evolution—i.e., that all deposited Devonian salt remained in situ during this time.

Reverse modelling (cf. Section 4.2) was carried out using the fictitious stratigraphic sections (corresponding to the three salt withdrawal scenarios) as the input data (Fig. 6b–d). Results are shown in Figs. 7–9. In all cases the syn-rift fault offsets have not been increased despite the increase in the total thickness of the Devonian syn-rift sequence.

The inferred β factors increase with increasing Devonian syn-rift thickness, as would be expected, and are greatest under the basin centre (Figs. 7d–9d). The reverse-modelled sections to base Carboniferous are shown in Figs. 7c–9c. In comparison with the results of the standard reverse-modelled section (Fig. 5a), these modified sections demonstrate much better fits to observed paleobathymetry at the beginning of the Carboniferous. The preferred model in this sense is the third one (salt withdrawal distributed during the Carboniferous and Early Permian), which shows an average paleobathymetry of some 400 m. However, this is still greater than observed depositional environments within the basin suggest, while the observed rift flank stratigraphy suggests sub-areal erosion. The discrepancy appears to be in the order of 400 m for both the basin and its northern flank. The error associated with this discrepancy may, however, be substantial, and it should only be regarded as a qualitative indicator of a misfit. As has been already mentioned a base Carboniferous 400 m misfit of paleobathymetry inferred from reverse post-rift modelling is equivalent in the forward sense to a need for an additional 400 m subsidence for the Carboniferous. A similar result was found by Kusznir et al. (1996) for the northwestern part of the DDB. In that study an additional Carboniferous subsidence of 300 m was required to obtain a good fit between observed and modelled sections. The regional distribution of Lower and Middle Carboniferous sediments within the East European Platform reveals that the platform was affected by regional subsidence at that time (Bronguleev, 1978). Moreover, the magnitude of the subsidence increased to the east towards the Uralian paleo-ocean. Thus, the geological data support the results of the reverse modelling. Most likely, the DDB was affected by subsidence related to regional tectonic forces that were not directly governed by lithospheric processes beneath the DDB itself.

Forward modelling of the syn-rift stage of basin formation using the flexural cantilever model has been carried out for Profile 4 using the modified stratigraphic sections according to the three scenarios outlined above. Results for the third scenario are shown in Fig. 10. Syn-rift basin geometry obtained by flattening "observed" stratigraphy to base Carboniferous is shown for comparison (dashed lines).

The flexural cantilever model has also been used to model post-rift basin development through the Early Carboniferous to the Bashkirian of the Middle Carboniferous. Post-rift thermal subsidence is driven by the β profile produced by forward syn-rift modelling (Figs. 7d–9d). Sediment fill at all stages is assumed to be to sea level. Compaction is included. The forward modelling results, corresponding to 50 Myr of post-rift basin evolution, are shown in Figs. 7b–9b where they are compared with the thickness

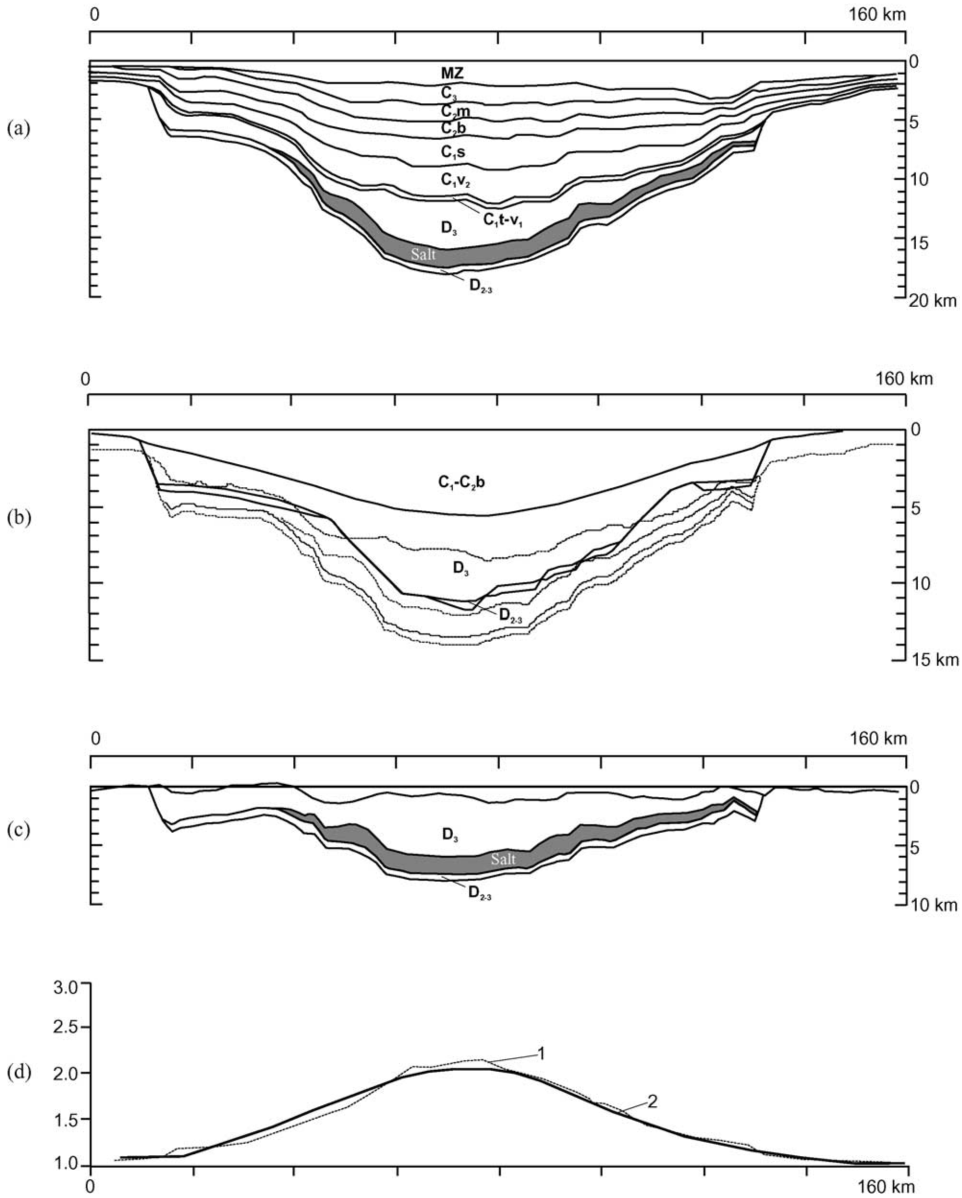


Fig. 7. Results of 2-D modelling taking into consideration the Early Permian withdrawal of Devonian salt. (a) The "observed" cross-section obtained by moving the Lower Permian layer into the Devonian sequence with the added salt layer shown as shaded. (b) Forward model of post-rift thermal subsidence to the top of Bashkirian (Middle Carboniferous) following Late Devonian rifting. (c) Reverse post-rift modelling to the top of the Devonian using a laterally varying β stretching factor. (d) The model inferred β stretching factor, describing distributed plastic stretching in the lower crust and mantle, across the basin.

of Lower Carboniferous–Bashkirian sequence reconstructed removing the influence of salt withdrawal. The model misfit for the first scenario decreases considerably in comparison with the conventional model described in the Section 4.3, but is still substantial (maximum 2.5 km) across the whole basin. The preferred scenario is again the third one, in which there was assumed to be three phases of

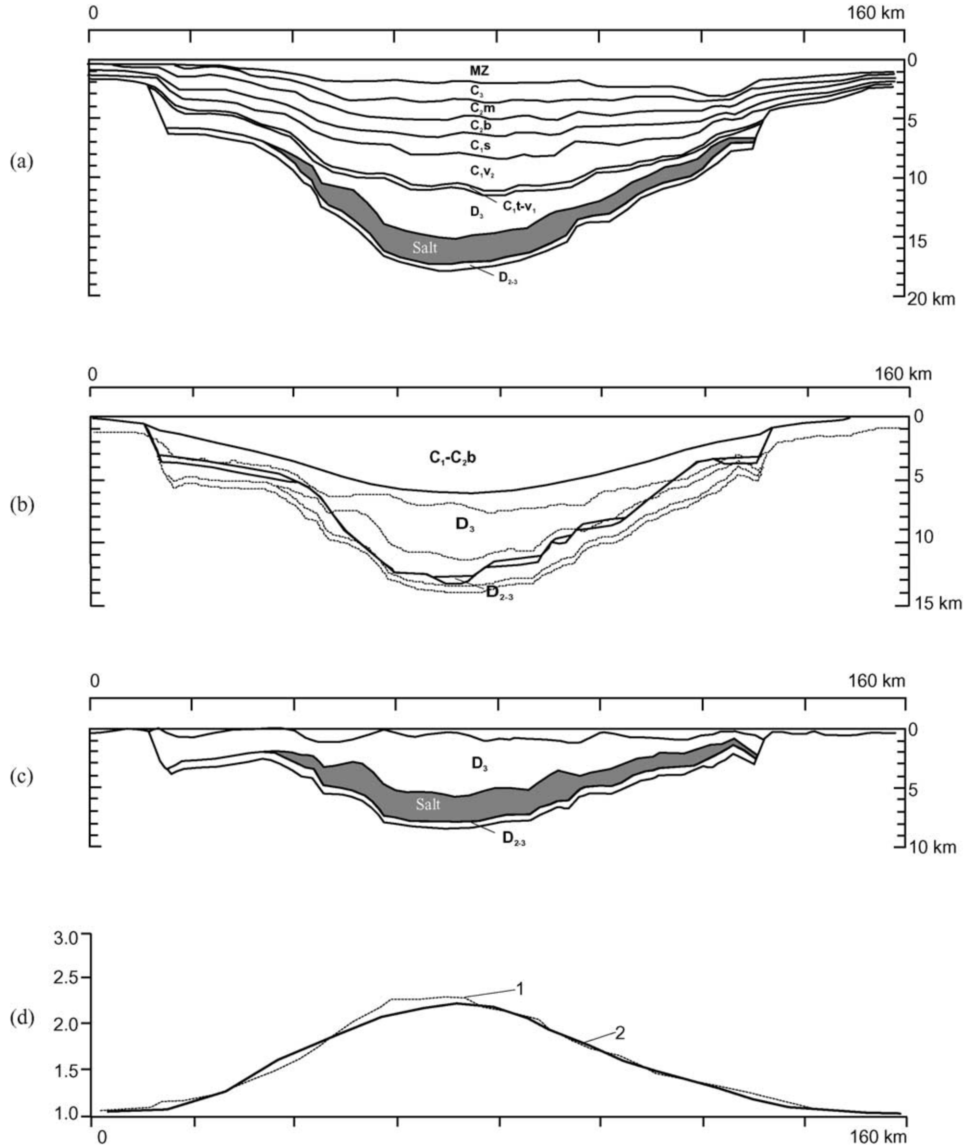


Fig. 8. As for Fig. 7 but taking into consideration Early Permian as well as Serpukhovian displacement of Devonian salt.

salt withdrawal. In this case, there is a satisfactory fit not only to syn-rift basin geometry and stratigraphy but also to the thickness of the Lower Carboniferous–Bashkirian sequence for the axial part of the basin (Fig. 9b). The deviation of the Carboniferous predicted thickness from the observed one varies from 0 to 0.5 km in the basin axial part, from 0.5 to 1.7 km within the pre-flank areas, and up to 1.5 km within the basin northern flanks. The model therefore fails to produce sufficient post-rift stratigraphy on the flanks of the basin.

Using the above mentioned geological observations that suggest a regional subsidence of the East European Platform during Early Carboniferous–Bashkirian times plus the predictions of the reverse model, a final, preferred, model has been calculated (Fig. 11a). This model includes 400 m of additional post-rift regional subsidence and gives a good fit not

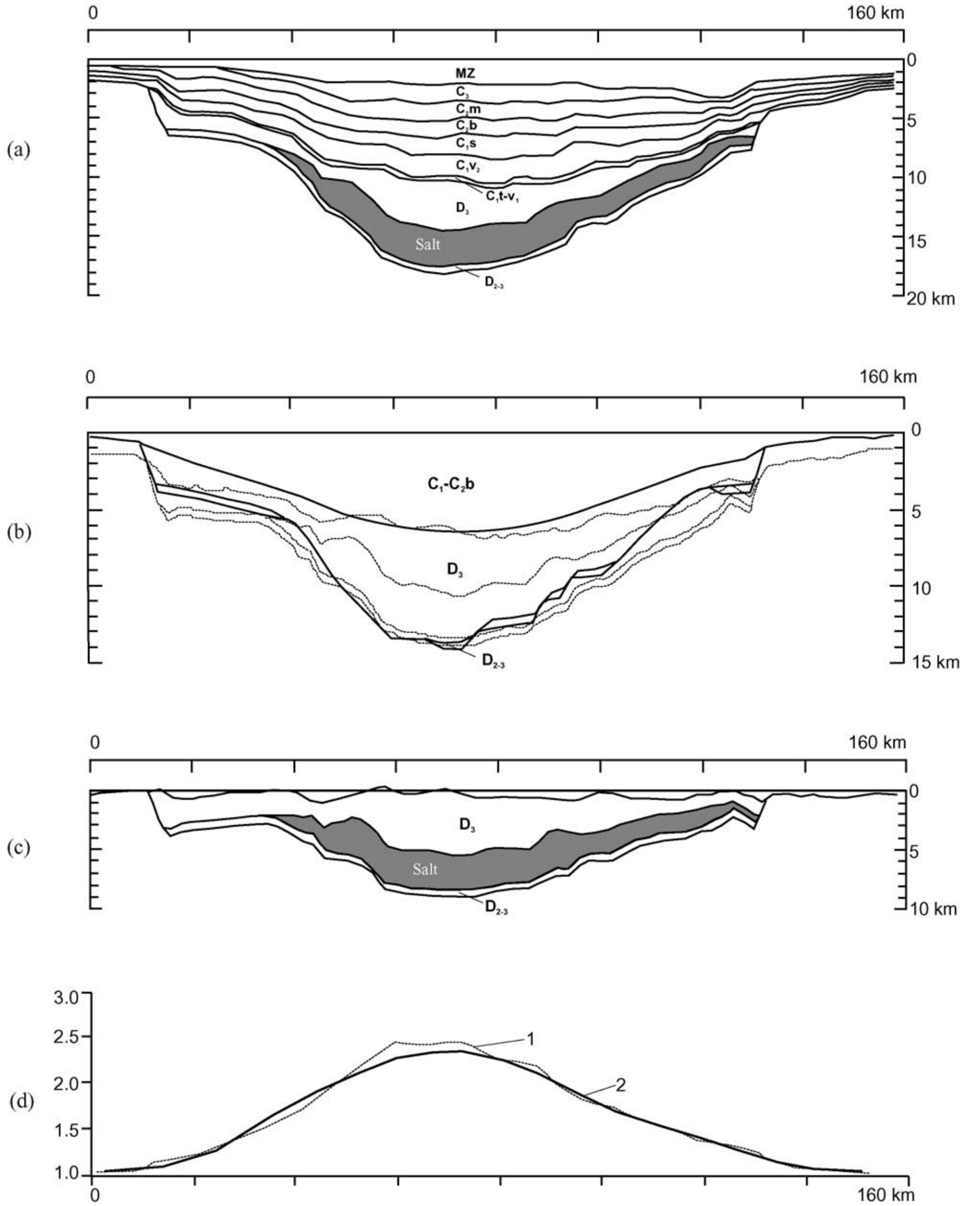


Fig. 9. As for Fig. 7 but taking into consideration Early Permian, Serpukhovian, and late Visean displacement of Devonian salt.

only to syn-rift basin geometry and stratigraphy (Fig. 10) but also to the thickness of the Lower Carboniferous–Bashkirian sediments for most of the profile with a standard deviation of ~ 200 m (Fig. 11a). An exception is the northern flank of the basin, where the deviation reaches 900 m, which will be discussed below.

Fig. 11b shows the results of post-rift forward modelling to top Carboniferous, corresponding to 70 Myr of post-rift basin evolution. In the axial part of the basin, Carboniferous sediments were not eroded during the Early Permian facilitating an easier comparison between modelled and observed thicknesses. The geological data suggest that during Moscovian–

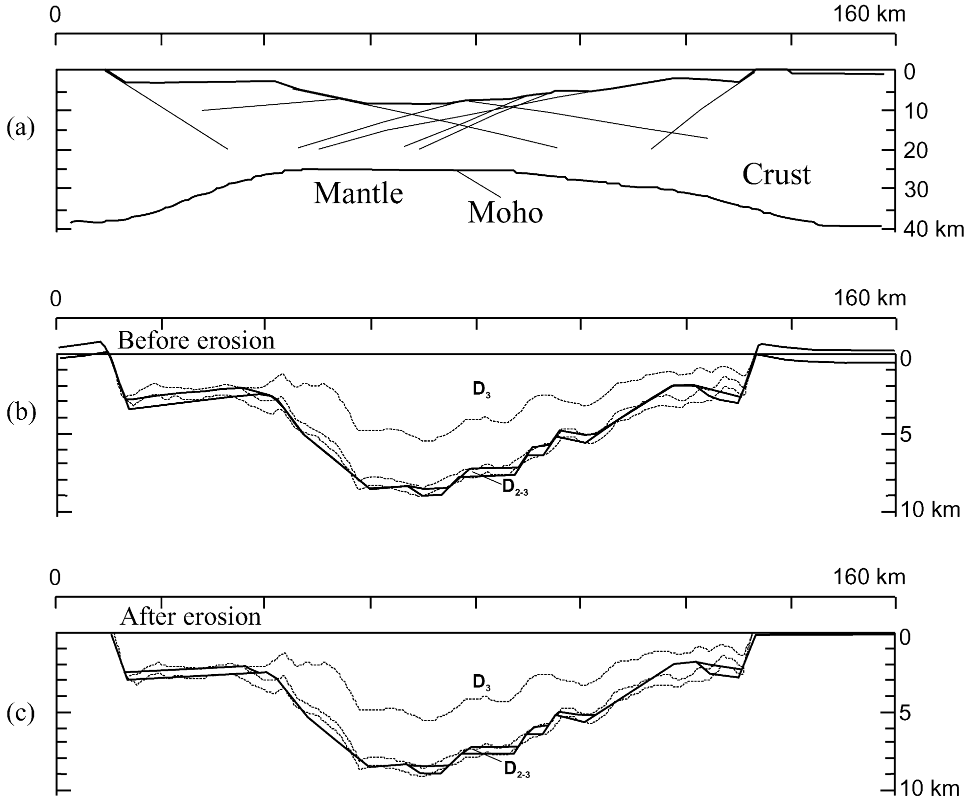


Fig. 10. Results of forward modelling for Profile 4 taking into account three phases of salt withdrawal. (a) Crustal section showing major upper crustal faults used in the modelling, fault-controlled syn-rift basin geometry and Moho uplift underneath the basin. (b) Vertically exaggerated section showing basin geometry and footwall uplift on the flanks of the basin before erosion. Pre-rift sediments are also shown. Observed thicknesses of pre-rift and syn-rift sediments after flattening and decompaction are shown for comparison (dotted lines). (c) As for (b) but after erosion to sea level of all topography, isostatic rebound and further iterative erosion and rebound. The degree of preservation of the pre-rift Devonian succession and rift basin thickness and geometry are consistent with observations.

Late Carboniferous times the East European Platform subsided as in the Early Carboniferous (Bronguleev, 1978). This observation has been taken into consideration and an additional 300 m of regional subsidence was added in calculating the model shown in Fig. 11b. The preferred model predicts the "observed" thickness of Carboniferous sediments very satisfactorily.

The total horizontal extension for the preferred syn-rift model is approximately 65 km. The maximum β factor is approximately 2.4, compared to 1.7 for the conventional forward modelling (Section 4.3), tending to unity on the basin flanks (Fig. 8d). The increase in maximum β is caused by the salt restoration procedure that has thickened the syn-rift sedimentary succession at the expense of the post-rift succession. The forward syn-rift model predicts footwall uplifts of some 800 m on the major bounding faults (Fig. 10b), eroded during the Late Devonian (Fig. 10c), and, in keeping with observations, an absence of pre-rift sediments on the basin margins.

In terms of crustal structure, the preferred syn-rift model predicts a maximum Moho uplift under the centre of the basin of approximately 15 km (Fig. 10a). After post-rift thermal subsidence and sediment loading, the predicted Moho shallowing is 4–5 km, which compares favourably with Moho depths observed using refraction seismology (Fig. 11c, dashed line), given an assumed initial crustal thickness of the order of 40 km.

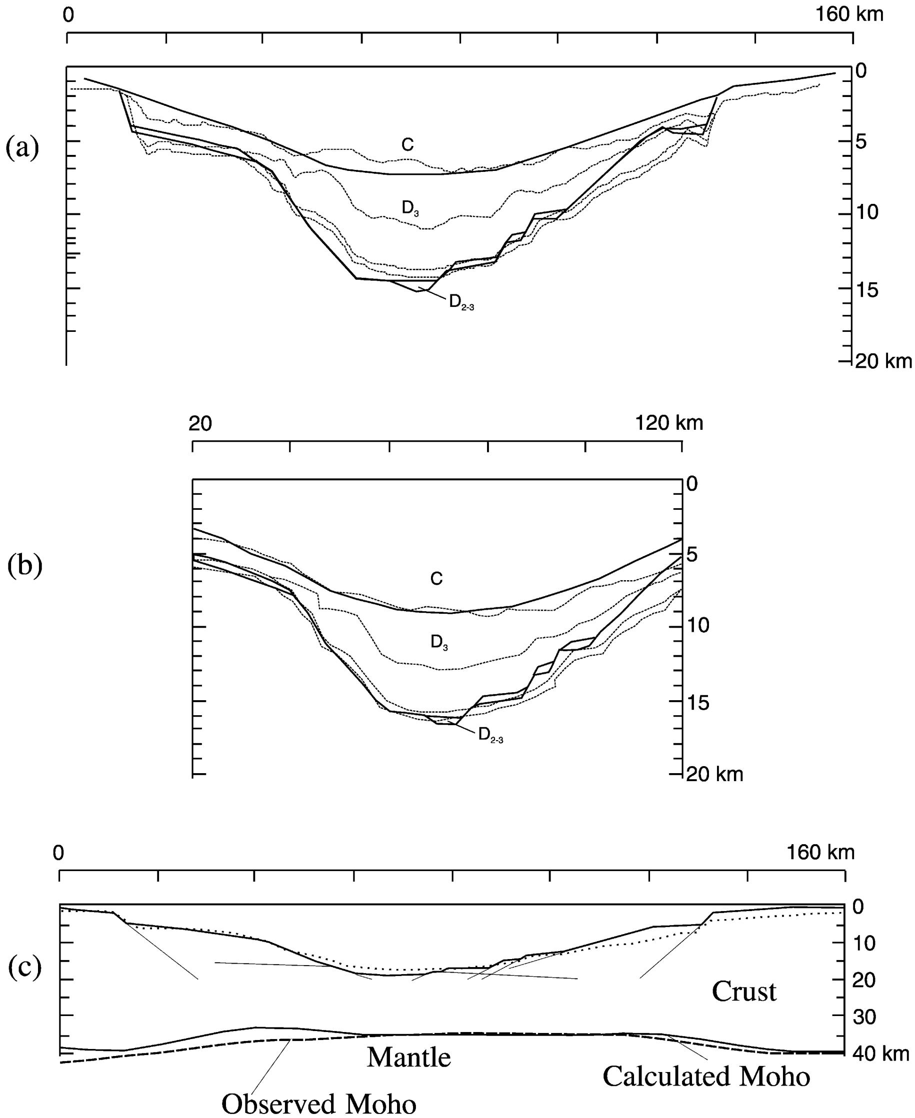


Fig. 11. Forward flexural cantilever model of post-rift thermal subsidence for Profile 4 taking into consideration three phases of salt withdrawal and regional subsidence of the East European Platform. (a) Forward model to the top of Bashkirian with 400 m of regional subsidence during the post-rift thermal subsidence phase. (b) Forward model for the axial part of the basin to top Carboniferous with 700 m of regional subsidence during the post-rift thermal subsidence phase. (c) Crustal section showing structure of the present-day basin and Moho. Moho depths observed using refraction/wide-angle reflection seismology are shown with the dashed line (Chekunov et al., 1992).

There is a good fit of the predicted and present-day thickness of sediments (Fig. 11c). The misfit does not exceed 1 km across the whole basin except in its northern part where it reaches ~ 1.5–2 km. This is rather surprising, on the one hand, because the modelling did not take into account two subsequent phases of uplift that affected the basin, significant especially in the southern part of the studied area. Thick Middle and Upper Carboniferous strata and Mesozoic strata were eroded during Early Permian and Late Cretaceous uplift events respectively. On the other hand, the model testifies to the importance considering the role of salt tectonics in creating additional accommodation space for Carboniferous sedimentation without necessitating extra tectonically driven subsidence (given the concurrent regional subsidence of the East European Platform).

The misfit in the thickness of post-rift sediments on the northern flank of the basin for Profile 4 (Fig. 11a) is not satisfactory. However, it may be that part of this area was involved in Devonian rifting, but that there is no record of this because of subsequent erosion of rotated basement blocks (e.g. Stovba and Stephenson, 1999; Stephenson et al., 2001). There are no geological data about this possibility for Profile 4. In contrast, geological data reveal this to have indeed been the case for Profile 3. This information has been used in Profile 3 to model syn-rift and post-rift stratigraphy.

The preferred results of forward and reverse modelling for Profile 3 are given in Fig. 12. The forward model gives a good fit to the thickness of the Lower

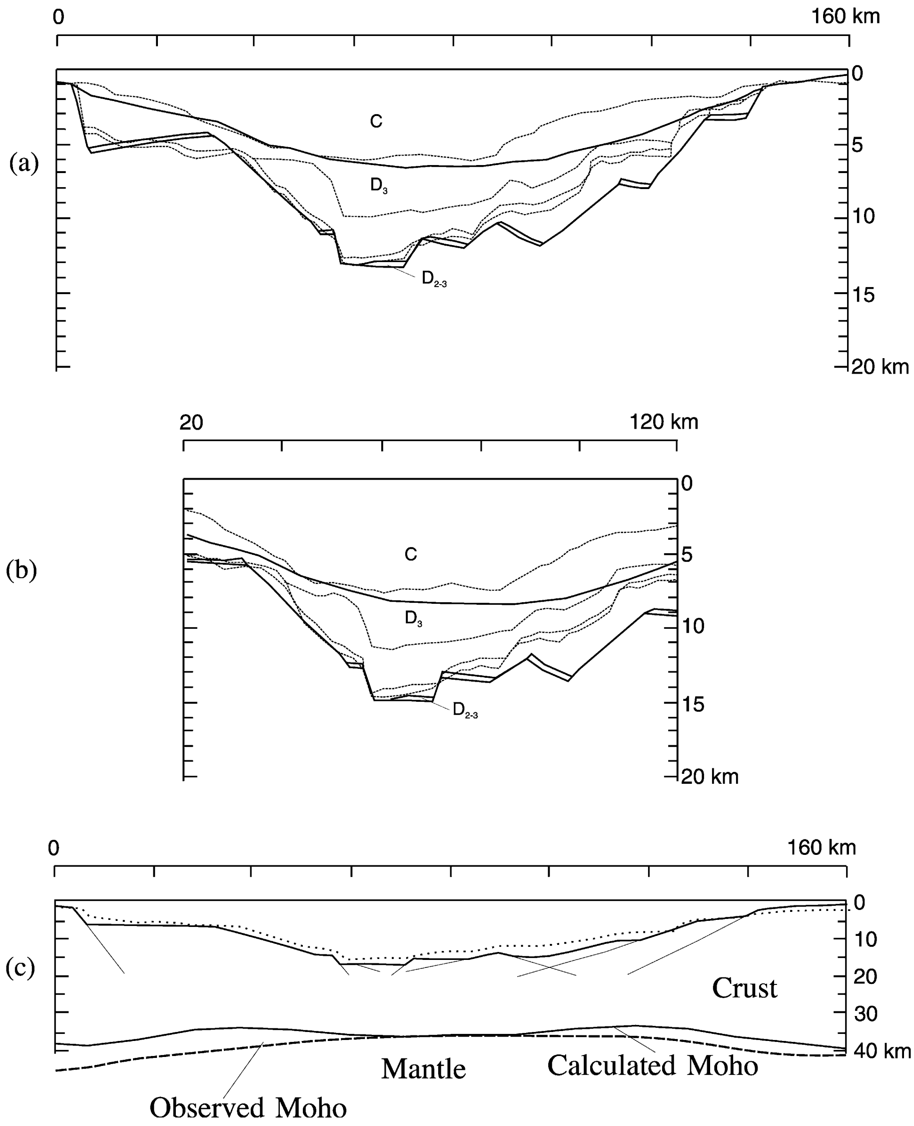


Fig. 12. As for Fig. 11 for Profile 3.

Carboniferous–Bashkirian sediments for most of Profile 3, including the north flank (Fig. 12a). Like the results for Profile 4, the model also satisfactorily replicates the total thickness of the Carboniferous sediments in the axial part of the basin where they were not eroded during the Early Permian uplift event (Fig. 12b). A good overall fit of modelled to present-day observed basin architecture and stratigraphy as well as Moho geometry has been achieved.

5. Summary and conclusions

The excessive thickness of post-rift sediments in the DDB compared to its syn-rift succession—in particular, the very thick Carboniferous sequence—has been generally considered to be problematic in modelling the tectonic controls on basin evolution (e.g. van Wees et al., 1996; Kusznir et al., 1996). Here, a scenario in which salt displacement—from the syn-rift succession to the post-rift succession—plays an essential role in the regional post-rift evolution of the basin leads to satisfactory tectonic modelling results without invocation of extraneous tectonic processes. Forward syn-rift modelling predicts Late Devonian extension across the south-eastern part the DDB to be approximately 65 km with a maximum β stretching factor of 2.4, twice that of the north-western part of the basin (cf. Kusznir et al., 1996). Syn-rift Moho uplift under the studied area is predicted by such modelling to be of the order of 15 km. This is reduced to 4–5 km for the present day by post-rift thermal subsidence and sediment infill, a prediction that coincides with existing crustal seismic data.

The excessive thickness of Carboniferous sediments in the south-eastern part of the DDB is explained in the proposed model by the effects of three superimposed processes. These are (1) post-rift thermal basin subsidence; (2) the withdrawal of the Devonian salt from the mother layer during three post-rift (Carboniferous and Early Permian) phases of salt diapirism; and (3) regional subsidence of the East European Platform during the Carboniferous. Salt withdrawal produces additional accommodation space for Carboniferous sediments and reduces the total thickness of the Devonian syn-rift sequence in the axial zone. According to such a model, the original thickness of the Devonian syn-rift succession would have been greater than is observed now — up to 7.5 km including as much as 3–3.5 km of salt that subsequently was extruded during post-rift salt diapirism phases. Up to 1.5–1.7 km of the Lower Carboniferous succession in the axial part of the basin is explained by subsidence driven by salt withdrawal through the stems of salt diapirs.

Forward and reverse post-rift modelling from the Early Carboniferous until Bashkirian implies further that regional subsidence of the order of 400 m was superimposed on the post-rift thermal subsidence. The preferred post-rift forward model, including this extra 400 m of regional subsidence, is able to predict the observed thickness of Lower Carboniferous–Bashkirian sediments. The forward model is also able to predict satisfactorily the observed thickness of the full Carboniferous succession in the axial part of the basin where sediments were not eroded during the Early Permian. The forward model predicts also the architecture of the present-day basin and the total thickness of the Palaeozoic and younger sediments even though no attempt was made to take into consideration two post-Carboniferous tectonic events producing basin uplift (especially in the southern part of the studied area). The results support the hypothesis that salt withdrawal may have played an important role in basin evolution during the Carboniferous (at least in the axial part) and that the effects of tectonically driven subsidence during the Carboniferous may be less important than previously suggested.

The modelling is poorly constrained in the sense that there is no rigorous geological evidence pertaining to what volume of Devonian salt may have been withdrawn from the mother layer during the Carboniferous and Early Permian. The inferences drawn from the modelling regarding additional syn-rift sedimentation and reduced post-rift tectonic subsidence can represent either an overstatement or an underestimate. In any case, the 2-D modelling results illustrate the potential importance of taking into account halokinetic processes when quantitatively modelling the tectonic evolution of the DDB or any other basin affected by significant salt displacements.

The results of the present study cannot explain all the characteristics of the tectonic evolution of the DDB. For example, the preferred models do not explain the slow subsidence rate during Tournaisian–earliest Visean times and, conversely, the accelerating subsidence rate beginning in the late early Visean. However, no consideration has been made of post-rift tectonic extensional reactivations that occurred during the Carboniferous (e.g. Stovba et al., 1996; Stovba and Stephenson, 1999) and which presumably affected the tectonic controls on basin evolution, perhaps significantly (cf. van Wees et al., 1996).

Is the salt withdrawal model also possibly relevant to the Donbas Foldbelt—the deformed part of the DDB lying to its south-east that displays an even thicker Carboniferous section? Perhaps not, given that most published accounts of the geology of the Donbas Foldbelt explicitly discount the possibility of salt accumulation there during the Late Devonian. Perhaps very much yes, given the recent opinions of Stovba (1998), Stovba and Stephenson (1999), and Stephenson et al. (2001), as well as earlier works (e.g. Stupakov, 1962) all of which do argue for the presence of Devonian salt in the Donbas Foldbelt. Stovba (1998) concluded that Devonian salt in the Donbas Foldbelt was displaced during the same late Visean and Serpukhovian phases of salt diapirism that are so clearly expressed elsewhere in the DDB.

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References

Bronguleev, V.V., 1978. Map of the thickness of the lower section Carboniferous system in the East-European craton. Ministry Geology of the RSFSR, Moscow, in Russian.

Chekunov, A.V., Gavrish, V.K., Kutas, R.I., Ryabchun, L.I., 1992. Dnieper–Donets paleorift. In: Ziegler, P.A. (Ed.), Geodynamic of Rifting, Vol. I. Case History Studies on Rifts: Europe and Asia. Tectonophysics, vol. 208, pp. 257–272.

Chirvinskaya, M.V., Sollogub, V.B., 1980. Deep structure of the Dnieper–Donets Aulacogen from Geophysical Data. Naukova Dumka, Kyiv, 178 pp., in Russian.

Dvorjanin, E.S., Samoyluk, A.P., Egurnova, M.G., Zaykovsky, N.Ya., Podladchikov, Yu., van den Belt, F.J.G., de Boer, P., 1996. Sedimentary cycles and paleogeography of the Dnieper Donets Basin during the late Visean–Serpukhovian based on multiscale analysis of well logs. Tectonophysics 268, 169–187.

Eisenverg, D.E., 1988. Geology and oil and gas occurrences of the Dnieper–Donets depression: stratigraphy. Naukova Dumka, Kyiv, in Russian.

Gavrish, V.K. (Ed.), 1989. Geology and Oil and Gas Potential of the Dnieper–Donets Depression: Depth Structure and Geotectonic evolution. Naukova Dumka, Kyiv, 208 pp., in Russian.

Izart, A., Briand, C., Vaslet, D., Vachard, D., Coquel, R., Maslo, A., 1996. Stratigraphy and sequence stratigraphy of the Moscovian in the Donets Basin. Tectonophysics 268, 189–209.

Izart, A., Briand, C., Vaslet, D., Vachard, D., Broutin, J., Coquel, R., Maslo, A., Maslo, N., Kozitskaya, R., 1998. Stratigraphy and sequence stratigraphy of the Upper Carboniferous and Lower Permian in the Donets Basin. In: Crasquin-Soleau, S., Barrier, E. (Eds.), Peri-Tethys Memoir 3: Stratigraphy and evolution of Peri-Tethyan platforms. Mém. Mus. Natn. Hist. Nat., Paris, vol. 177, pp. 9–33.

Korenevskiy, S.M., Bobrov, V.P., Supronyuk, K.S., Khrushov, D.P., 1968. Halogenic formations of the north-west Donbas and Dniepr–Donets Basin. Nedra, Moscow, 240 pp., in Russian.

Kusznir, N.J., Ziegler, P.A., 1992. The mechanics of continental extension and sedimentary basin formation: a simple-shear/pure-shear flexural cantilever model. Tectonophysics 215, 117–131.

Kusznir, N.J., Marsden, G., Egan, S.S., 1991. A flexural cantilever simple-shear/pure-shear model of continental extension. In: Roberts, A.M., Yielding, G., Freeman, B. (Eds.), The Geometry of Normal Faults. Geological Society of London, Special Publication, 56, pp. 41–61.

Kusznir, N.J., Roberts, A.M., Morley, C.K., 1995. Forward and reverse modelling of rift basin formation. In: Lambiase, J.J. (Ed.), Hydrocarbon Habitat in Rift Basins. Geological Society of London, Special Publication, 80, pp. 33–56.

Kusznir, N.J., Stovba, S.M., Stephenson, R.A., Poplavsky, K.N., 1996. The formation of the northwestern Dniepr–Donets Basin: 2-D forward and reverse syn-rift and post-rift modelling. Tectonophysics 268, 237–255.

McKenzie, D.P., 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters 40, 25–32.

Nadin, P., Kusznir, N.J., 1995. Palaeocene uplift and Eocene subsidence in the northern North Sea Basin from 2-D forward and reverse stratigraphic modelling. Journal of the Geological Society of London 152, 833–848.

Roberts, A.M., Yielding, G., Kusznir, N.J., Walker, I., Dorn-Lorez, D., 1993. Mesozoic extension in the North Sea: constraints from flexural backstripping, forward modelling and fault populations. In: Parker, J.R. (Ed.), Petroleum Geology of North West Europe: Proceedings of the 4th Conference. The Geological Society of London, London, UK, pp. 1123–1136.

Saintot, A., Privalov, V., Zhikaliak, M., Brem, A., the EUROPROBE/INTAS team, 1999. Some kinematic indicators for the tectonic evolution of the Donbas Fold-and-thrust belt (Ukrainian part). EUROPROBE TESZ, Pancardi and Georift Workshop, Tulcea, Romania. Romanian Journal of Tectonics and Regional Geology 77 (Supplement 1), 83.

Sclater, J.G., Christie, P.A.F., 1980. Continental Stretching: an explanation of the post mid-Cretaceous subsidence of the Central North Sea Basin. Journal of Geophysical Research 85, 3711–3739.

Stephenson, R.A., Stovba, S.M., Starostenko, V.I., 2001. Pripyat–Dniepr–Donets Basin: implications for dynamics of rifting and the tectonic history of the northern Peri–Tethyan platform. In: Ziegler, P.A., Cavazza, W., Robertson, A.H.F., Crasquin-Soleau, S. (Eds.), Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins. Mém. Mus. Natn. Hist. Nat., Paris, vol. 186, pp. 369–406.

Stovba, S.M., 1998. Dnieper–Donets Depression: features of the Late-Visean and Serpukhovian tectonic motion activation stages. Geophysical Journal, Kyiv, 9–21 (in Russian); translated version in Geophysical Journal 18, 655–674.

Stovba, S.M., Maystrenko, Yu.P., 2000a. Features of SE Dniepr–Donets Basin formation by 2-D forward and reverse tectonic modelling. Geophysical Journal 22 (2), 80–94 (in Russian).

Stovba, S.M., Maystrenko, Yu.P., 2000b. Some features of Dniepr–Donets Basin formation during the rift stage. In: Shpak, P.F. (Ed.), Topical Problems of Oil and Gas Geology, vol. 2. Carbon Publishing House, Kyiv, pp. 70–79, in Russian.

Stovba, S.M., Stephenson, R.A., 1999. The structural relationship of the Donbas Foldbelt with the uninverted Donets segment of the DDB, Ukraine. Tectonophysics 313, 59–83.

Stovba, S.M., Stephenson, R.A., in press. Style and timing of salt tectonics in the Dniepr-Donets Basin (Ukraine): correlation with extensional and compressional tectonic events. Marine and Petroleum Geology.

Stovba, S.M., Stephenson, R.A., Dvorianin, E., 1995. Dnieper–Donets Basin, Ukraine: main observations from regional seismic reflection profiles. Comptes Rendus de l'Académie des Sciences, Paris, Série II. Fascicule a, Sciences de la Terre et des Planètes 321 (12), 1103–1110.

Stovba, S.M., Stephenson, R.A., Kivshik, M., 1996. Structural features and evolution of the Dniepr–Donets Basin, Ukraine, from regional seismic reflection profiles. Tectonophysics 268, 127–147.

Stupakov, V.P., 1962. About the origin of broken stratum in the Kamensky region of the northern part of the Donbas. In: Collected Papers on the Geology of Gas Areas of the USSR. Gostoptekhizdat, pp. 195–199.

van Wees, J.-D., Stephenson, R.A., Stovba, S.M., Shimanovsky, V.A., 1996. Tectonic variation in the Dniepr–Donets Basin from automated modelling of backstripped subsidence curves. Tectonophysics 268, 257–280.