MODELS OF THE EVOLUTION OF THE DNIEPR-DONETS BASIN (UKRAINE)

STEPHENSON, R.A., Netherlands Research School of Sedimentary Geology, Vrije Universiteit, Amsterdam, Netherlands.

Summary

In the Dniepr-Donets Basin (DDB), a Late Palæozoic rift basin within the East European Platform in Ukraine, syn- and post-rift basin evolution has been modelled along cross-sections using four different modelling techniques. The basic geological input in each case is the same. This is the present-day geometry of the basin from abundant borehole data and, using these, interpreted and depth-converted regional seismic reflection profiles. The first modelling method is 1-D, modelling tectonic subsidence from well data. Local isostatic response is assumed but the thermo-mechanical effects of superimposed extensional events affecting a layered lithosphere are calculated. The other models are 2-D. In the first of these, the basic rheological framework is one of a uniform thin elastic plate of given strength that flexes. Displacements on pre-defined faults are allowed and these displacements are incorporated into the mechanical equilibrium of the problem. The modelling parameter is the lithosphere-"stretching factor" β. The third method utilises a continuous, non-faulted, elastic thin plate (with a defined flexural rigidity) that deforms not only from vertical loads associated with sediment, thermal, and isostatic buoyancy loading but also from horizontal loading by tectonic stresses. The nominal parameter set comprises crustal and subcrustal stretching factors δ and β and the level of lithosphere "necking". In the fourth model presented, the governing rheology is also elasticity but the crust is modelled as a block-structured medium rather than as a thin plate. The method incorporates syn-sedimentary and/or erosional faulting of an upper crustal layer. Accumulated strain (displacement) across the defined fault surfaces is the main modelling parameter. Results from the different modelling methods are compared in order to make conclusions about the processes governing formation of the DDB rift basin. It is concluded that most important modelling parameter – at least for modelling the DDB (which can be inferred to have resulted from "active" rifting processes) – is the capability to incorporate inhomogeneous lithosphere thinning during rifting.

Introduction

The DDB is an intracratonic rift basin lying in the south-eastern part of the East European Platform (e.g. Chekunov et al., 1992; Stephenson et al., 1993). The structure of the rift is well-known from numerous regional seismic reflection profiles (Stovba et al., 1996; Stovba and Stephenson, 1999), as shown on Fig. 1. Depth-converted interpretations of four of these are shown in Fig. 2.

The main rifting phase forming the DDB occurred in the Late Devonian. Crustal scale marginal and axial faults with large throws formed at this time, accompanied by rapid subsidence that produced grabens and half-grabens within the basin, and uplift and erosion of the rift shoulders, especially on the southern flank. Faulting fractured the crystalline basement into blocks of dimensions 2-5 km and less; uplifted blocks separate major syn-rift depocentres formed at this time (Stovba et al., 1996).

Fig. 2 shows that within the rift Devonian sediments overlie crystalline basement while on the rift shoulders the Devonian succession is generally absent with Carboniferous rocks unconformably overlying basement. Significant volumes of volcanic (Wilson and Lyashkevich, 1996) and saliferous rocks are found in the syn-rift succession. The latter were subsequently modified by diapirism; salt stocks more than 10 km high occur (Stovba et al., 1996). The thickness of the Devonian succession varies substantially, often over very short distances, with the maximum thickness being about 4 km.

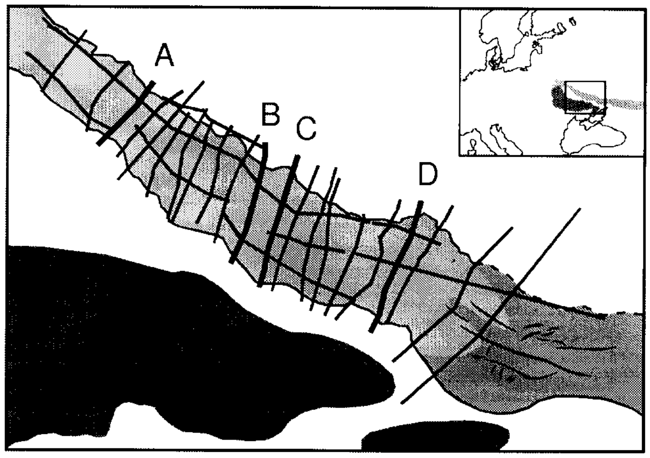

Fig. 1. Setting of the DDB in Europe (main rift zone with light shading) and locations of regional seismic reflection lines, those shown in Fig. 2 thickened and labelled A-D.

Fig. 2 also shows that post-rift basin development, commencing at the beginning of the Carboniferous, is characterised by the formation of a large thermal sag basin (Stovba et al., 1996). Carboniferous and younger units cover the rift flanks and increase in thickness towards the rift axis. The post-rift depocentral axis closely corresponds to the rift axis. Maximum sediment thickness, accumulated during both syn- and post-rift stages of basin development, ranges from 2-6 km in the north-west to 15-19 km in the south-east.

The ratio of post- to syn-rift sediment thickness is large, however, and this is one of the key tectonic issues in the subsidence history of the DDB. The post-rift subsidence appears too great to be explicable by typical thermo-extensional basin models (e.g. McKenzie, 1978). An understanding of the tectonic driving mechanism is further complicated by the effects of a number of tectonic reactivations during the post-rift phase of development; these corresponded with the most active periods of salt movements and increase in severity towards the south-east (Stovba et al., 1996; Stovba and Stephenson, 1999).

Subsidence models of the Dniepr-Donets Basin

Numerous wells and stratigraphic sections in the DDB have been analysed for tectonic subsidence, using standard "backstripping" techniques to remove sediment decompaction, paleobathymetry, and local isostatic loading effects (e.g. Steckler and Watts, 1978). Stephenson et al. (1993), van Wees et al. (1996), Nikishin et al. (1996), and Stephenson et al. (1997) published results for the

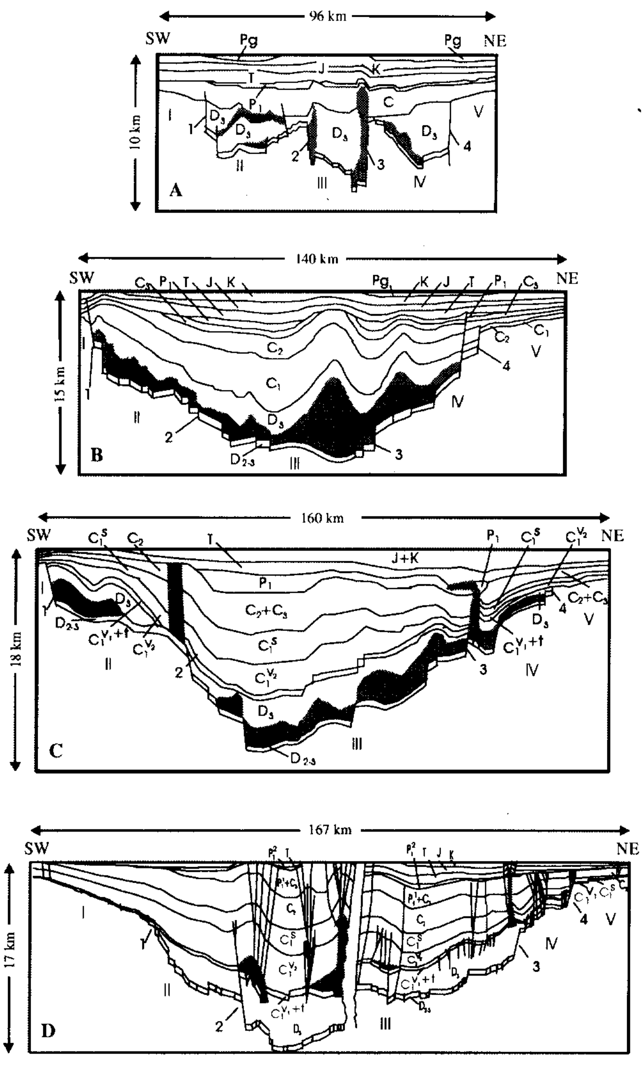

Fig. 2. Depth-converted cross-sections of the DDB from seismic profiles located in Fig. 1, from Stovba et al. (1996) and Stovba and Stephenson (1999).

DDB. Examples are shown in Fig. 3. Several 2-D flexural backstripping and forward and inverse modelling studies were also carried out on a number of profiles in the north-western DDB (Kusznir et al., 1996; Starostenko et al., 1999; Poplavskii et al., in press).

An automated 1-D backstripping and inverse modelling technique was employed by van Wees et al. (1996) to calculate and analyse tectonic subsidence curves for 66 wells (including synthetic wells) over a wide area of the DDB. Areas affected by salt movements were avoided. Tectonic subsidence curves for four example wells and predicted tectonic subsidence for a preferred model out of several that were considered are shown in Fig. 3. The curves are characterised by intermittent episodes of rapid subsidence and periods of slow subsidence and/or uplift. Accelerations correspond with episodes of active tectonics, corroborated by structural relationships seen on seismic reflection profiles.

The Late Devonian syn-rift phase as well as Carboniferous post-rift reactivation phases (shaded panels on Fig. 3) were considered by van Wees et al. (1996) in modelling the observed subsidence data. Post-rift subsidence was explained satisfactorily by the superposition of an Early Carboniferous thermo-extensional reactivation onto the thermal structure derived from Late Devonian rifting. Requisite syn-rift lithospheric stretching factors for the DDB as a whole are in the range 1.0-1.34, increasing generally to the south-east. The Early Carboniferous reactivation phase was best incorporated into the modelling results by considering inhomogeneous lithosphere thinning with two independent "stretching" factors, δ and β, for the crust and sub-crustal lithosphere separately. These are in the ranges 1.0-1.51 and 1.01-10, respectively, also increasing from north-west to south-east. Broadly, δ characterises "mechanical" thinning and β "thermal" thinning of the lithosphere. There are two significant problems with these model results *vis-à-vis* the geological history of the DDB. One is that the inferred crustal stretching during the main, Late Devonian, rift phase is less than that of the Early Carboniferous tectonic event although the geological evidence shows that the latter is only a minor reactivation of the former. The other is that profound thermal perturbation of the lithosphere during the Carboniferous is implied (β as great as 10, meaning that the lithosphere is thinned to as little as 10% of its original thickness), compared to the Devonian. However, in contrast to this, the magmatic activity associated with the DDB appears predominantly to be syn-rift, not post-rift.

Kusznir et al. (1996) employed the flexural cantilever technique, involving faulting of the upper crust and ductile pure-shear of the lower crust during rifting (e.g. Kusznir and Ziegler, 1992), to model one profile crossing the north-western DDB (Fig. 2A). The modelling method specifically incorporates the flexural effects of faulting on adjoining hanging- and footwall blocks. This leads to uplift and erosion on the rift flank, in particular on the outermost footwall block. The width of this flank uplift depends on the flexural rigidity but, in general, the regional basin subsidence as a whole also depends on the flexural rigidity. In reconciling these two effects, Kusznir et al. (1996) found that a satisfactory fit of stratigraphic relationships on the flanks and outer flanks of the basin necessitated that Late Devonian rifting be accompanied by a regional uplift (or lowering of relative sea level) of the order of 300-m. This is because the 300-m thick pre-rift stratigraphic

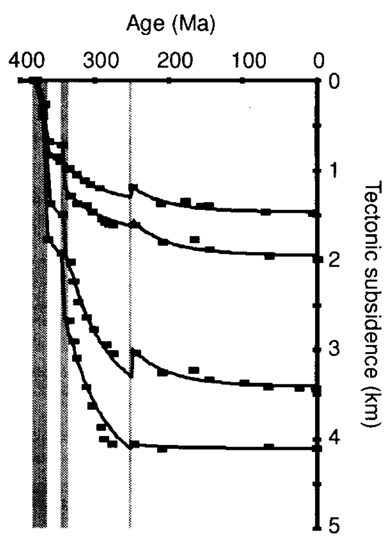

Fig. 3. Tectonic subsidence (boxes) derived from backstripping and 1-D model results (lines) for several wells in different parts of the DDB (deepening to the south-east), from van Wees et al. (1996).

succession of the DDB, found preserved beneath the syn-rift sediments within the rift itself, is absent from the rift flanks entirely. The maximum β calculated by Kusznir et al. (1996) was 1.3. However, it was found that this magnitude of syn-rift stretching in itself was insufficient to drive the requisite (mainly Carboniferous) post-rift subsidence of the basin. Rather, an "extra" regional subsidence (or relative sea level rise), augmenting post-rift thermal subsidence during the Carboniferous, was introduced to provide the accommodation space necessary to match the observed sedimentary thickness. The inferred magnitude of this post-rift regional subsidence was, coincidentally, about 300-m, the same as the regional uplift required to explain the older syn-rift basin stratigraphy.

The coincidence of the independently inferred magnitude of syn-rift uplift with post-rift subsidence suggested a genetic relationship and Kusznir et al. (1996) proposed the dynamic effects of a mantle "plume". These could have indeed been transient, resulting in non-thermal topographic uplift during the active rift phase, decaying away thereafter, as the main plume centre migrated away. That the magmatic history of the DDB requires elevated mantle temperatures during its initial formation (e.g. Wilson and Lyashkevich. 1996) supported this interpretation of the subsidence modelling results. No further testing of the dynamic uplift/subsidence hypothesis was carried out, for example, by modelling other basin cross-sections. Problematic is that the relative increase in the post-rift Carboniferous basin succession to the south-east compared to the syn-rift Late Devonian succession. Application of the same dynamic topography model to cross-sections to the south-eastern DDB would require greater and greater "uplift decay" – regional subsidence – during the Carboniferous. However, there would be no independent argument that the magnitude of dynamic uplift during the syn-rift phase – about 300-m required to erode the pre-rift sediments on the distal parts of the rift shoulders – should increase similarly. Further, the distribution of magmatic rocks in the DDB suggests that the main "plume" centre is in the north-west, not the south-east where subsidence is greater (Wilson and Lyashkevich, 1996; Stephenson et al., in press).

Poplavskii et al. (in press) modelled the subsidence development of two DDB cross-sections in the same part of the basin as Kusznir et al. (1996), near profiles A and C in Fig. 1. They implemented an inverse modelling method based on the forward model of Kooi and Cloetingh (1992). The lithosphere has flexural strength, as in the flexural cantilever method of Kusznir, but faults are not explicitly built-in. However, the degree of crustal – or upper lithosphere – thinning (e.g. δ-factor) can be different from the degree of sub-crustal lithosphere thinning (e.g. β-factor), as in the 1-D method of van Wees et al. (1996), and a lithosphere "necking level" can be specified. This is the depth at which extension focuses during rifting in the absence of isostatic effects (e.g. Braun and Beaumont, 1989). The effects of in-plane stresses could also be included but this was not done in the case of the DDB models. Poplavskii et al. (in press) easily found satisfactory models to explain the subsidence and stratigraphic geometries along both profiles taking into account only the effects of the Late Devonian rift phase. Maximum δ-factors were 1.6-1.8, approximately consistent with the rift extension seen on the respective seismic sections, while maximum β-factors were about 5 and 7. Although the inferred β-factors are quite large, it is significant that the post-rift DDB could be modelled without requiring additional Carboniferous tectonic reactivations – as inferred by van Wees et al. (1996) – or extraneous regional subsidence – as inferred by Kusznir et al. (1996). The results further implied a shallow "necking level", generally ascribed to relatively weak lithosphere rather than cold, strong, cratonic lithosphere. The profound thermal perturbation of the lithosphere indicated by the inferred high β-factors in the DDB could possibly also explain the presence of weak lithosphere and shallow necking there.

Starostenko et al. (1999) modelled the same profile as Kusznir et al. (1996) but instead of using an elastic thin plate for the uppermost, strong part of the lithosphere they used a "block-structured medium" (cf. Starostenko et al., 1996). The geometry and displacements through time along pre-defined faults, based on the actual geological structure and stratigraphic relations seen on the seismic profiles, were incorporated into the model. Thus, the syn-rift upper crustal extension is in effect introduced as a modelling boundary condition rather than inferred as a modelling result. Concurrently, the sub-crustal part of the rifting process is introduced explicitly in terms of a perturbation to the sub-rift lithosphere temperature field of variable intensity, size, shape, and duration (Fig. 4). The characteristics of the lithosphere thermal perturbation required to best explain the syn- and post-rift basin evolution is the model result, analogous to finding a best-fitting β-factor. Starostenko et al. (1999), like Poplavskii et al. (in press) but using an entirely different modelling approach, determined that the DDB, at least in its north-west part, can be modelled as the result of a single Late Devonian rifting phase associated with a large thermal perturbation of the lithosphere.

Discussion

All of the modelling methods discussed have features that permit a quantitative explanation of the excess post-rift sedimentary fill of the DDB in comparison to the degree of observed syn-rift extension. Thermo-extensional reactivations during the Carboniferous were introduced by van Wees et al. (1996) whereas Kusznir et al. (1996) implemented extraneous regional subsidence to provide the necessary Carboniferous sediment accommodation space. Neither of these methods had the capability of separating mechanical extension of the uppermost lithosphere during the main rifting phase in the Late Devonian from the concurrent,

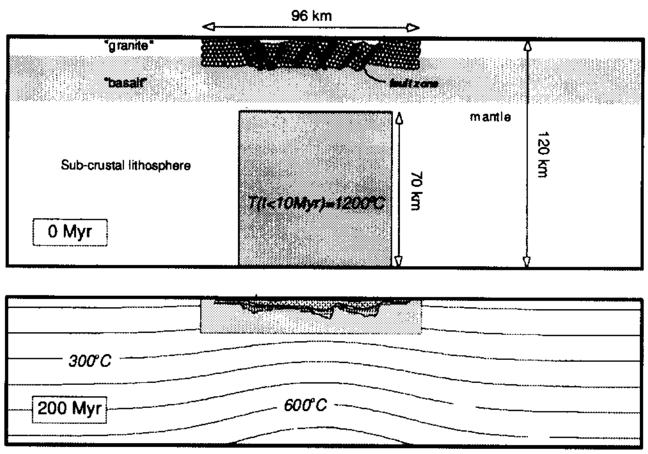

Fig. 4. Model configuration at the end of rifting (0 Myr) and lithosphere temperatures after 200 Myr in the Starostenko et al. (1999) model of profile A (Fig. 1).

thermally and/or mechanically induced thinning of the sub-crustal lithosphere. Non-homogeneous lithosphere "stretching" or thinning is not allowed by Kusznir's method, which concentrates more on modelling the stratigraphic and structural relationships developed around upper crustal faults forming during extension. In principle, the method of van Wees allows heterogeneous thinning of the lithosphere during rifting. In practice, however; because of a lack of sufficient data for the DDB at the onset of rifting, there are too many degrees of freedom in the inverse mathematical formulation of the problem to solve for independent syn-rift β- and δ-factors.

The models of Poplavskii et al. (in press) and Starostenko et al. (1999) are very different in their formulation and parameterisation. Nevertheless, the physics that leads to satisfactory modelling results in essentially the same in each. This is the development of a large thermal anomaly in the lithosphere (or, equivalently, the shallowing of the lithosphere-asthenosphere boundary) during the Late Devonian rifting phase that contributes, by its decay, to rapid post-rift subsidence in the Carboniferous. This is achieved by the one common element of these two modelling methods – that the degree of lithosphere thinning is not linked directly to the degree of upper crustal extension as in the original McKenzie (1978) formulation of the rift basin problem.

Conclusions

Different rift basin modelling methods are tuned to different features involved in the processes governing rifting and thermo-extensional basin evolution. Application of different models to the same structural and stratigraphic datasets, as has been done for the DDB in Ukraine, helps to identify weaknesses in the individual methodologies being used. In turn, as in the case of the DDB, it can lead to more robust conclusions about the key processes dominating rifting in a given basin. The ability to decouple explicitly the mechanical processes affecting the upper crust from the thermal processes dominating in the sub-crustal lithosphere appears to be an important element in quantitatively modelling rift basins. For the DDB, it may be concluded that the thermal thinning of the lithosphere during Late Devonian rifting was relatively much greater than the concomitant mechanical thinning of the upper crust. "Active" rifting processes were involved in the formation of the DDB

Acknowledgements

The author acknowledges the vast amount he has learnt from and the enjoyment of collaboration with his many Ukrainian colleagues during the last years.

References

Braun, J. and Beaumont, C., 1989. Dynamical models of the role of crustal shear zones in asymmetric continental extension. Earth and Planetary Science Letters, 93: 405-423.

Chekunov, A.V., Gavrish, V.K., Kutas, R.I., and Ryabchun L.I., 1992. Dniepr-Donets paleorift. In: P.A. Ziegler (Editor), Geodynamics of Rifting, Vol. I. Case History Studies on Rifts: Europe and Asia. Tectonophysics, 208: 257-272.

Kooi, H. and Cloetingh, S., 1992. Lithospheric necking and regional isostasy at extensional basins, 2: stress-induced vertical motions and relative sea-level changes. Journal of Geophysical Research, 97: 17573-17591.

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

Kusznir, N.J. and 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.

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

Nikishin, A.M., Ziegler, P.A., Stephenson, R.A., Cloetingh, S., Furne, A.V., Fokin, P.A., Ershov, A.V., Bolotov, S.N., Korotaev, M.V., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., and Shalimov, I.V., 1996. Late Precambrian to Triassic of the East-European Craton: dynamics of basin evolution. Tectonophysics, 268: 23-63.

Poplavskii, K.N., Podladchikov, Yu.Yu., and Stephenson, R.A., in press. 2D inverse modeling of sedimentary basin subsidence. Journal of Geophysical Research.

Starostenko, V.I, Danilenko, V.A., Vengrovitch, D.B., Kutas, R.I., Stovba, S.M., Stephenson, R.A., and Kharitonov, O.M., 1999. A new geodynamical-thermal model of rift evolution, with application to the Dnieper-Donets Basin, Ukraine. Tectonophysics, 313: 29-40.

Starostenko, V.I., Danilenko, V.A., Vengrovitch, D.B., and Poplavskii, K.N., 1996. A fully dynamic model of continental rifting applied to the syn-rift evolution of sedimentary basins. Tectonophysics, 268: 211-220.

Steckler, M.S. and Watts, A.B., 1978. Subsidence of the Atlantic-type continental margin off New York. Earth and Planetary Science Letters, 4: 1-13.

Stephenson, R.A. and the EUROPROBE Intraplate Tectonics and Basin Dynamics Working Group, 1993. Continental rift development in Precambrian and Phanerozoic Europe: EUROPROBE and the Dnieper-Donets rift and Polish Trough basins. Sedimentary Geology, 86: 159-175.

Stephenson, R.A., Stovba, S.M., and Starostenko, V.I., in press. Pripyat-Dniepr-Donets Basin: implications for dynamics of rifting and the tectonic history of the northern peri-Tethyan platform, in P.A. Ziegler, W. Cavazza, and A.H.F. Robertson (eds.), Peri-Tethyan Rift/Wrench Basins and Passive Margins, Peri-Tethys Memoir 6, Mémoires du Muséum National d'Histoire Naturelle.

Stephenson R A., van Wees, J-D., Stovba, S.M. and Shimanovsky, V.A. 1997. Numerical 1D modelling of the tectonic subsidence of the Dniepr-Donets Basin in the framework of the McKenzie model of continental lithosphere stretching. Geophysical Journal, Kyiv: 25-41 (in Russian)

Stovba, S.M and Stephenson, R.A., 1999. The Donbas Foldbelt: its structural relationship with the uninverted Donets segment of the Dniepr-Donets Basin, Ukraine. Tectonophysics, in press.

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

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

Wilson, B.M. and Lyashkevich, Z.M., 1996. Magmatism and the geodynamics of rifting of the Pripyat-Dnieper-Donets rift, East European Platform. Tectonophysics, 268: 65-81.