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An Attempt to Predict Lithospheric Extension Parameters within McKenzie's Model

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Abstract

The sedimentary infilling of extensional basins when analyzed via the back-stripping approach can provide a record of the subsidence history associated with basin formation. Comparison of this empirical information with the data on basin dynamics based on one-dimensional McKenzie extensional modelling provides a means of deriving estimates of crustal and lithospheric (as a whole) thicknesses and β value (coefficient of extension). Divergence between modelled and observational results when changing the variable parameters of lithospheric thicknesses and coefficient of extension are minimized by a least squares method. The resultant closest approach between the model calculations are those from backstripping analysis of basin evolution constrain the lithospheric and crustal thicknesses and β parameter to the most appropriate to the particular sedimentary basin. This technique has been applied to the Danish basin, the Dnieper-Donets aulacogen, and the Welsh basin. The results for the Danish basin provide a close match to those from a deep seismic survey.

Key words: sedimentary basins, lithospheric extension, back-stripping analysis, modelling

1. Introduction

Processes of lithospheric extension and thermal contraction form the basis of modern dynamic models of crustal rifting. The substantiating ideas for lithospheric extension were suggested by *Vening Meinesz* (1950), *Artem'ev and Artyushkov* (1971), *Bott* (1971), *Fuchs* (1974) and *Whiteman et al.* (1975), whereas *Sleep* (1971), *Sleep and Snell* (1976), *Haxby et al*. (1976), *Watts and Ryan* (1976), *Parsons and Sclater* (1977) emphasised the role of thermal contraction in respect to the lithospheric condition and behaviour. *McKenzie* (1978) developed a generalized geodynamic rifting model involving the lithospheric extension and thinning, with ascent of hot asthenosphere, followed by restoration of isostatic balance, cooling and thermal contraction. Such model versions based on finite extension of the lithosphere at various rates during the initial spreading stage (*McKenzie*, 1978; *Jarvis and McKenzie*, 1980; *Cochran,* 1980; *Sheplev and Reverdatto*, 1994; *White*, 1994; *Sheplev and Reverdatto*, 1998) have been considered as giving a sufficiently reasonable approximation to the actual processes and good agreement with empirical data (*Jarvis and McKenzie*, 1980; *Friedinger,* 1988; *White,* 1994; *Reverdatto et al.,* 1995). The reason for the success of these model versions is that after the spreading stage, basin subsidence and heat flow evolution proceed on a sufficiently long time scale that they are independent of the extension mode during the initial rifting and are largely controlled by asthenosphere cooling and thermal contraction. The applicability of these approximate model versions is confirmed by close agreement between the simulation results and the observed dynamics of tectonic subsidence inferred from the structure of sedimentary sequences in well-studied rift basins. Thus basin infill provides a unique record of the tectonic development (*Galloway,* 1989; *Stephenson et al.,* 1993; *Reverdatto et al.,* 1995) and gives a chance to verify some geodynamic theories. In the present paper, we try to use that possibility for a approximate determination of unknown parameters of the lithospheric extension.

2. Extensional modelling of sedimentary basin evolution

It is commonly supposed that sediment thicknesses accumulated during different time periods correlate with the dynamics (rate) of lithosphere subsidence. At a basic level, high rates of sediment accumulation occur due to rapid subsidence, and low rates are due to slow subsidence. Thus sedimentary architecture and age of discrete horizons can provide independent information on the dynamics of tectonic subsidence. Such data can be refined by correcting for changes in the layer thicknesses due to decompaction of the rocks after lithostatic unloading – the so-called backstripping procedure (*Sclater and Christie*, 1980).

We have studied the evolution of three sedimentary basins using both approaches within the framework of McKenzie's model and the data on sedimentation dynamics through the stratigraphic – lithologic character of basin infills. The BASTA (BAsin Subsidence and Temperature Analysis) software package (*Friedinger*, 1988; *Friedinger et al*., 1991; *Reverdatto et al*., 1995) was used in the 1-D modelling of subsidence and thermal evolution of these basins. The software performs the following procedures: reverse/forward subsidence dynamics modelling based on observed information on the sedimentation, theoretical simulation of subsidence dynamics on the basis of McKenzie's model linking the earth's crust downsinking with the extension of lithosphere, and the comparison of these results in the form of estimation of minimized deviation between both approaches. The sequence of sedimentary layers with corrected thicknesses and densities of the rocks is calculated for each time step, and from that the depth-duration pattern emerges. Coincidentally with the subsidence modelling, the calculation of sediment heating at different depth is carried out to represent the paleotemperature evolution.

For calculations, the average physical rock parameters were used: lithosphere density – 2.8 g×cm^{-3}, upper mantle density – 3.33 g×cm^{-3}, thermal conductivity of the lithosphere – 0.03 J×cm^{-1} ×s^{-1}×C^{-1}; coefficient of thermal expansion – 3.3×10^{-5} C^{-1}, equilibrium heat flow through the lithosphere – Q_e = 1.4×10^{-6} HFU (heat flow unit) including 0.6×10^{-6} HFU due to radioactive decay. The physical properties of sedimentary rocks (sandstone, siltstone, shale, limestone, etc.) varied as follows: porosity – from 25% to 60% depending on the composition and decreasing with depth according to linear or exponential laws, mineral and rock densities were from 2.5 to 2.8 g×cm^{-3}, thermal conductivities – 0.02 to 0.04 J×cm^{-1}×s^{-1}×C^{-1}. Other parameters include: temperature of the upper mantle 1350°C, temperature of the earth's surface 10°C; density of seawater –1.03 g×cm^{-3}, its thermal conductivity – 5.98 J×cm^{-1}×s^{-1}×C^{-1}. For simplicity it was assumed that β was depth – independent. The lithospheric in-elastic rheology was ignored as well; this facilitated the execution of the task very much but could lead to uncertainty or misinterpretation. Proper allowance must be made when improving the method.

Danish basin

The Danish basin is a NE-SW oriented rift basin of North Jylland, Denmark infilled with a series of marine sedimentary rocks including sandstone, shale, siltstone and carbonate, ranging from Permian to Recent (*Vejbaek*, 1989). These rocks unconformably overlie an Early Paleozoic sequence that is regarded as the upper part of the rift basement. Deep seismic investigations (*EUGENO-S Working group*, 1988) show the crustal thickness in the Danish basin region is 26 km at present, 6 km of which is Permian and younger sediments. Southward the crustal thickness increases up to 36 km, and northward – up to 40 km. This indicates that the initial crust thickness before spreading was no less than 36 km. *Vejbaek* (1989) has used the estimate of 37 km as a pre-rift crustal thickness. The subsidence evolution and sediment accumulation for the Danish basin are shown in Fig. 1a along with the evolution of paleoisotherms calculated on the basis of conductive heat flow and thermal conduction of the rocks during crustal subsidence. The commencement of rifting was assumed to be coincident with the start of asthenosphere cooling, and in the course of cooling the heat flow through the lithosphere was reduced by approximately one-fourth: from 1.96 to 1.41 HFU.

Dnieper-Donets aulacogen

The Dnieper-Donets is a 60–170 km wide rift that trends in a NW-SE direction for 1300 km across the southwestern region of the East European Platform. This paleorift formed on a Precambrian basement as a long-lived geological structure, that has an earlier late Proterozoic history followed by a main Devonian-Carboniferous rifting stage (*Gavrish*, 1987; *Aisenverg*, 1988; *Ermakov et al.*, 1988; *Chekunov et al.*, 1990; *Stephenson et al.*, 1993). The simulation of the rift evolution was performed using the Lokhvitskaya depression in a central part of the basin, about 150 km east of Kiev as the type section (*Chekunov et al.*, 1992). This is infilled with Devonian and Carboniferous siltstone, sandstone, limestone, shale, quartzite and some evaporites. The stratigraphic relationships of the sequence indicate relatively rapid subsidence in the Upper Devonian and slow tectonic subsidence in the Carboniferous associated with asthenosphere cooling and thermal contraction. The subsequent Meso-Cenozoic sedimentary sequence (up to 2 km thick) transgresses across the rift edges and was not connected with the rifting process. Deep seismic investigations indicate that crustal thickness in the vicinity of and underlying the Dnieper-Donets paleorift is 30–45 km (*Chekunov et al.*, 1992). This linear rift structure is not manifested by relief at the level of the Moho discontinuity suggesting some asthenospheric flow during Meso-Cenozoic time. The same physical parameters as used for the Danish basin were used for the Dnieper-Donets aulacogen; the resultant subsidence evolution and sediment accumulation pattern are shown in Fig. 1b. The heat flow value during the rift evolution reduced from 3.5 to 2.1 HFU.

Welsh basin

The Welsh basin in the UK, although not a rift structure, has been interpreted as a marginal trough associated with oceanic subduction and extension of the continental crust and lithosphere within the back-arc area (*Kokelaar et al*., 1984a,b; *Bevins et al.,* 1995). Such back-arc spreading involves thinning of the crust and lithosphere linked to asthenospheric upwelling and so the one-dimensional McKenzie-tpe model can be applied to this setting. The Welsh basin was developed on continental Precambrian crust in a NE-SW trend that was determined by faults restricting the north-western and south-eastern margins of trough. It is infilled with a marine sedimentary succession consisting chiefly of mudstone and turbiditic sandstone accumulated continuously during Lower Paleozoic times. At the basin margins, sedimentation included shallow-water clastics or carbonates. During the Ordovician, extensive volcanism occurred with an initial island-arc petrochemistry that evolved in time and space across the basin to a dominant acid-basic bimodal association. Inversion of the Welsh basin began towards the end of the Silurian (*Kokelaar et al.,* 1984a,b; *Bevins et al*., 1995). The modelling of Welsh basin evolution was undertaken on the basis of stratigraphic-lithologic column for the Cader Idris area in North Wales (*Cocks et al*., 1971; *Williams et al*., 1972). The heat flow value was constant for the development of the basin at c. 1.95 HFU. The calculation results for basin evolution and sediment accumulation pattern are given in Fig. 1c.

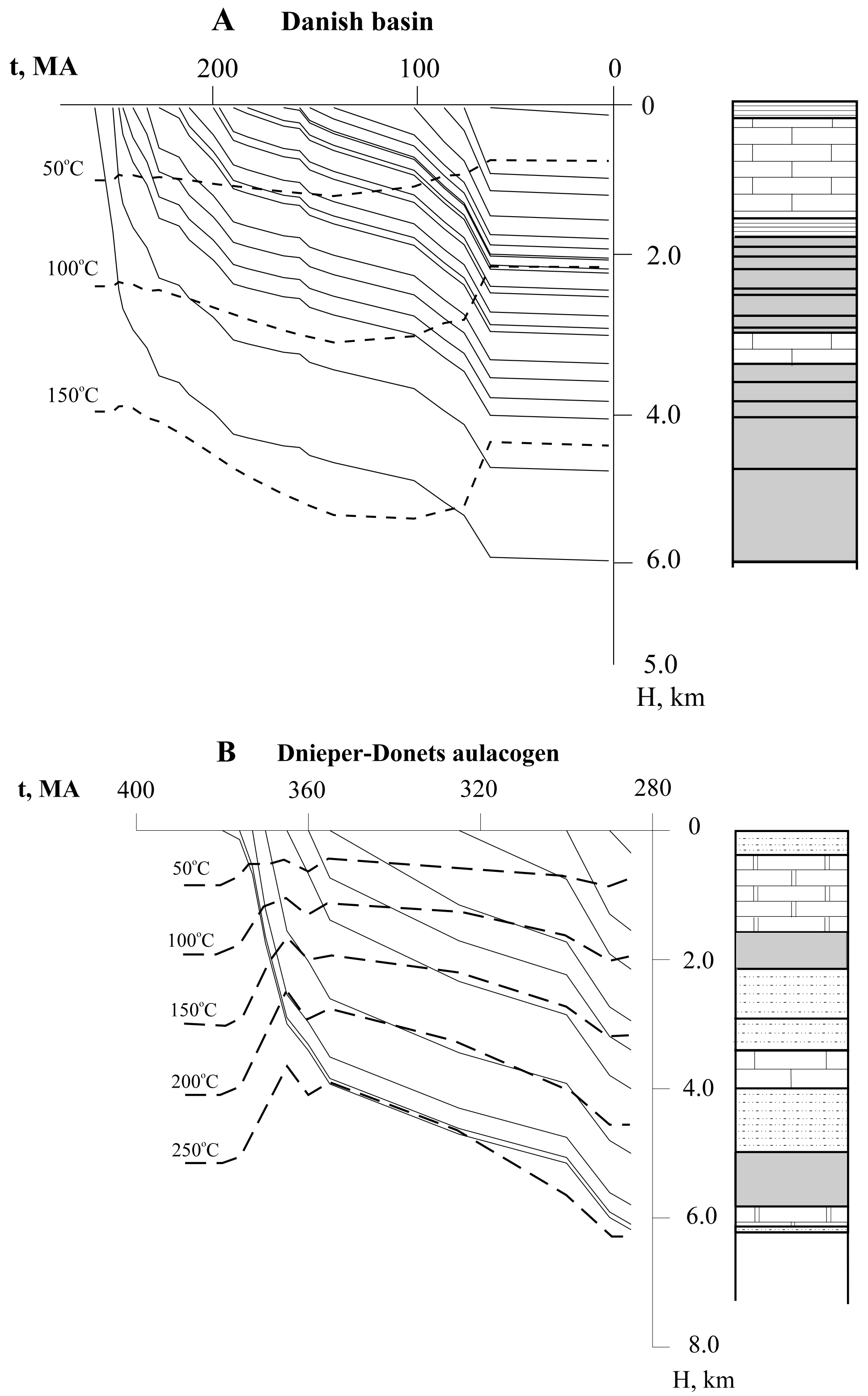

Fig. 1a-c. (Continues on next page.) The evolution models of subsidence and sediment accumulation for the Danish basin (A), the Dnieper-Donets aulacogen (B) and the Welsh basin (C). Start of extension stage coincided with the beginning of asthenosphere cooling. Solid lines are the boundaries of layers of different ages and compositions; dashed lines show behaviour of isotherms. The simplified stratigraphic columns placed on the right sides depict the sequences of sedimentary rocks with the generalized lithologic characteristics. Designations: 1 – sandstone, gritstone, conglomerate; 2 – mudstone; 3 – siltstone; 4 – evaporites including salt, gypsum, anhydrite, dolomite, etc.; 5 – limestone, marl, chalk; 6 – tuff, tuffite, ignimbrite; 7 – basalt, volcanic breccia. T – time, MA; H – depth, km.

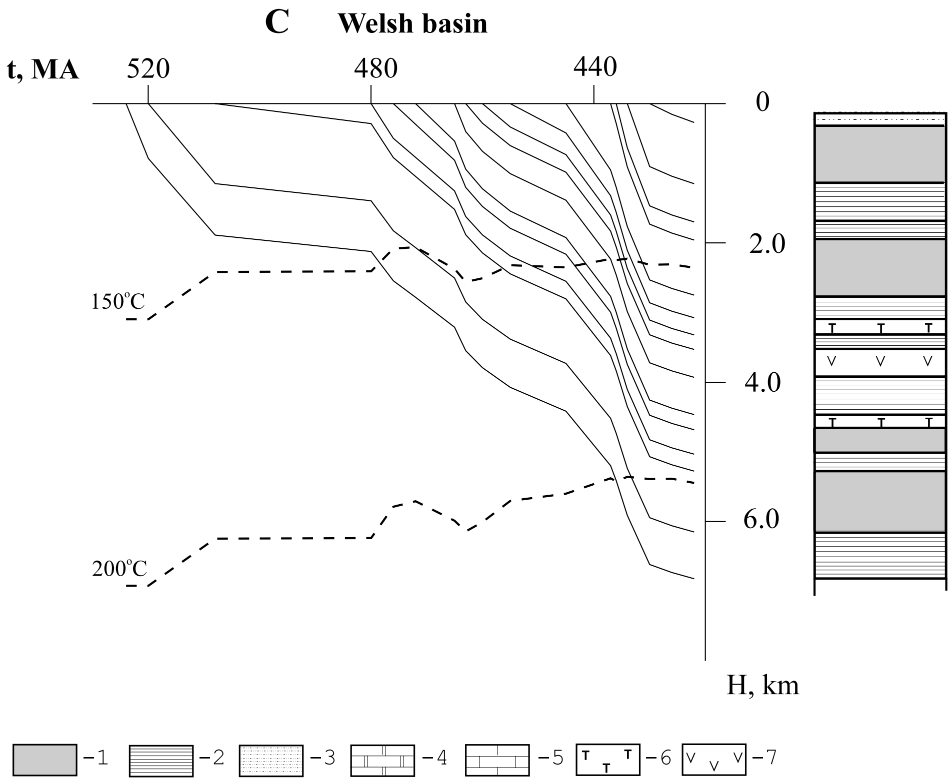

Fig. 1a–c. (Continuation from previous page.)

3. *Results matching to derive lithospheric extension parameters*

Using the concept of genetic stratigraphic sequence analysis and recognising the complex interplay between tectonic and sedimentary controls (*Galloway*, 1989), we have attempted to predict the crustal and lithospheric thicknesses and coefficient of extension for basin formation. First a simulation of subsidence dynamics on the basis of a rifting McKenzie model, using the input parameters given above, is undertaken to produce a theoretical subsidence (depth-time) curve calculated for a particular coefficient of extension as well as thicknesses of the crust and lithosphere with due regard to isostatic balance and thermal contraction/expansion of the rocks. Then lithospheric (reverse/forward) subsidence dynamics is calculated by the back-stripping (*Sclater and Christie*, 1980) of consecutive parts of the stratigraphic sequence; in so doing an empirical curve is derived from the evolution of gradually unloaded basement by successive removal of the overlying sedimentary layers. Three of the main parameters in the calculations of the rifting model, coefficient of extension and initial crustal and lithospheric thicknesses, were varied through reasonable range, giving a great variety of estimates which were then compared to the results derived from the back-stripping approach. Comparison of results for basin subsidence regarding the two different approaches was then undertaken using a least square method (*Friedinger*, 1988). Close matching of the theoretical curve to the empirical one was achieved by an iterative procedure whereby the difference between the curves was estimated by a least square approach to minimize the deviation of the sum of squares. This procedure covered all the three unknown variables: thickness of the lithosphere, that of the crust and coefficient of extension; given two quantities of three were variable, the third being the best constant, the best estimate for each pair of parameters was successively found. In this way, the best fitting model estimate, i.e. the final estimate that is most similar to the data derived from the back-stripping procedure was obtained. In earlier works using McKenzie's model for subsidence calculations, the lithospheric thickness was always taken as a known constant (125 km or somewhere in the range of 100–150 km). We have first considered this parameter as a unknown variable and attempted to determine it.

Table 1. Presumed values of extension parameters of the lithosphere.

Basins	Coefficient of lithospheric extension (β)	Initial thickness of the crust (km)	Initial thickness of the lithosphere (km)
Danish	1.37–1.41	36–38	80–95
Dnieper-Donets	2.0–3.0	30–35	140–175
Welsh	1.2–1.5	35–40	uncertain (in the range of 120–270)

The results of this approach for the three basins are demonstrated in Fig. 2a–c, and the intervals of best evaluations of the lithospheric and crustal thicknesses and coefficients of extension are given in Table 1. The prediction for the Danish basin can be tested against that of *Vejbaek* (1989) who deduced from deep seismic information that the pre-rift crustal thickness at the basin site was no less than 36–37 km. *Balling* (1985) and *Calcagnile and Scarpa* (1985) determined from seismological data the lithospheric thickness in the basin to be c. 90 km; both values are within the intervals calculated here (Table 1). However, crustal thickness determined from seismological data in the Dnieper-Donets aulacogen was 30–45 km (*Chekunov et al*., 1992); the differences with our estimates can be explained by a posterior deformation of the Moho surface and the mantle flows. The evaluation obtained for initial lithospheric thickness in the Welsh basin was uncertain.

4. Conclusions

In this paper using well-known technique (back-stripping analysis and McKenzie's model), the simplest approach was employed to obtain some estimates for the crustal and lithospheric thickness and coefficient of extension. A search of generalized relationship between parameters when tackling the problem led to the elimination from consideration of several important circumstances: depth-dependent character of the extension coefficient, temperature- and rheology-dependent nature of the lithospheric thickness, time-dependent property of the lithospheric strength, etc. The implicit subordination to McKenzie's model for all sedimentary basins discussed here and for the underlying lithospheric plates has been declared in spite of questions concerning the Welsh basin. Because of this, the suspictions can be arisen in respect of some estimates mentioned above. Notwithstanding all these doubts, the results derived in their classical sense as introduced by *McKenzie* (1978) are of interest particularly in order to demonstrate a unevident potentiality of the model.

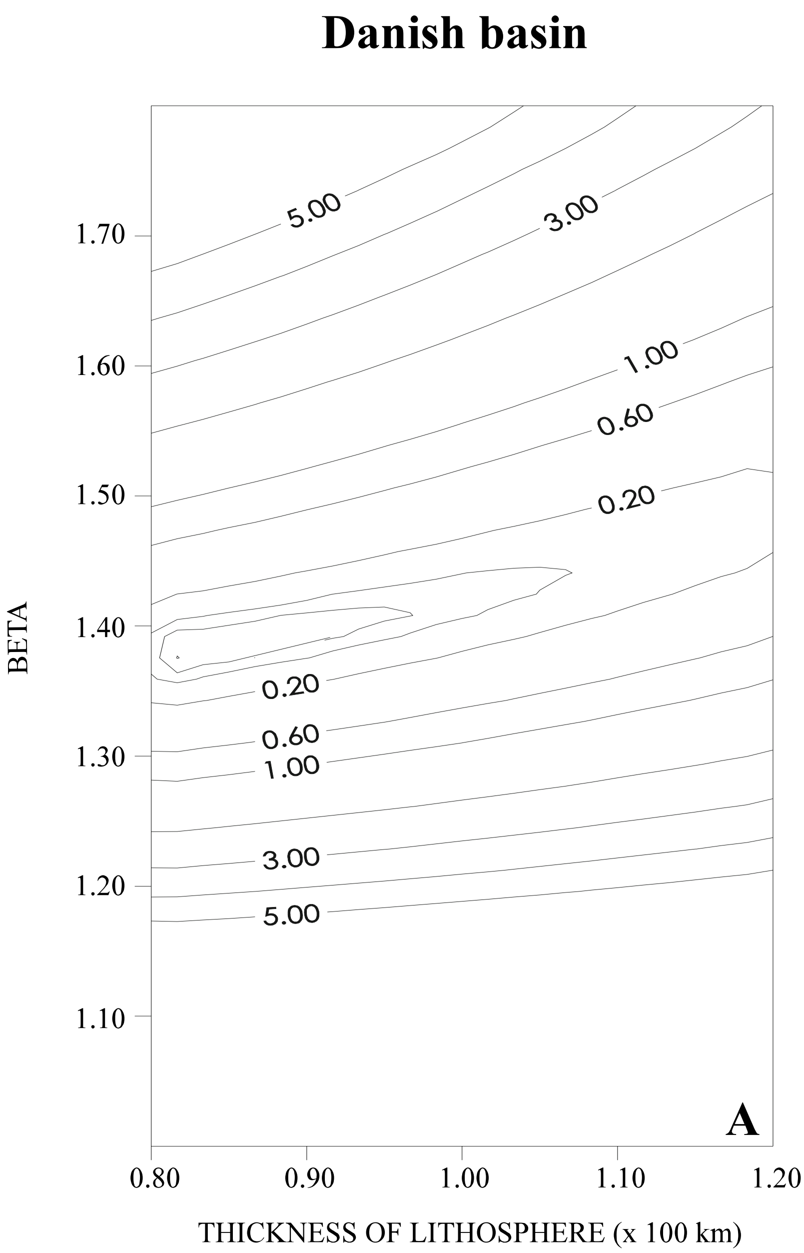

Fig. 2a–c. (Continues on next page.) The minimization diagrams for detecting the best fitting model / observation agreements as regards the Danish basin (A), the Dnieper-Donets aulacogen (B) and the Welsh basin (C). The isolines show equal deviation sum of squares when comparing the modelling and empirical results for basin evolution; beta (β) - coefficient of extension.

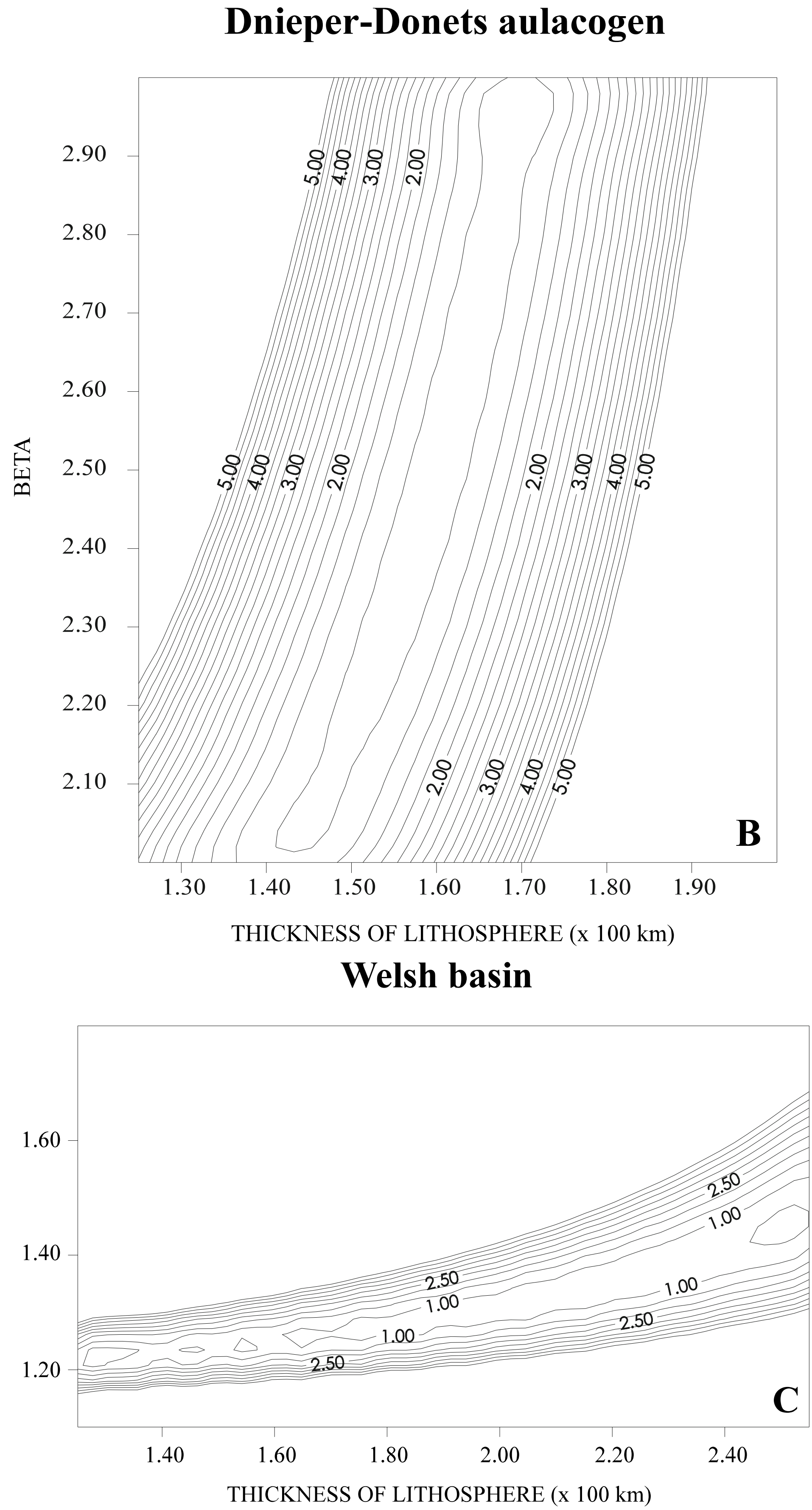

Fig. 2a-c. (Continuation from previous page.)

So, comparisons between extensional basins on the basis of McKenzie-type extensional models and back-stripping approaches provide a means, by divergence minimization, to estimate the parameters of lithospheric and crustal thicknesses and coefficient of extension. Convergence between the results for these two approaches using iteration by least squares minimization of the deviation of the sum of squares thus provides a means to constrain estimates of these parameters. On the whole, the results for three basins, Danish, Dnieper-Donets and Welsh, give the range of extension coefficients from 1.2 to 3.0, and wide variation in crustal and total lithospheric thicknesses.

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