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Quantitative subsidence analysis and forward modelling of the Vienna and Danube basins: thin-skinned versus thick-skinned extension

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Abstract

We present the results of a quantitative study of the tectonic evolution of the Vienna and Danube basins by comparing tectonic subsidence histories derived from backstripping of more than 90 wells from Slovakia, Hungary and Austria, with the predictions from forward tectonic modelling. Subsidence analysis and forward modelling, using a modified, non-uniform, extension model address the tectonic relations between different depocentres and the nature of tectonic subsidence.

We derived stretching values for the Vienna basin between 1.04 and 1.30 for the crustal extension (δ) and between 1.00 (in the northern part) and 1.60 (southern part) for the lithospheric extension (β). The Danube basin is characterized by crustal extension values (δ) between 1.09 and 1.30 and lithospheric extension values (β) between 1.00 (northern part) and 1.60 (southern part).

The Vienna basin shows a trend from thin-skinned extension in the northwestern part to whole lithospheric extension in the central-southern part. The subsidence history of the northwestern part of the Danube basin also reflects a thin-skinned extensional basin formation mechanism. The central and southern parts of the Danube basin show an important component of lithospheric extension.

The basin evolution is strongly influenced by the rotating stress field through Miocene times, expressed in different phases of fault reactivation that are observed in the subsidence history.

1. Introduction

The Vienna and Danube basins are situated in the Eastern Alpine, Western Carpathian and Pannonian area junction (Fig. 1). They can be characterized as intramontane basins with a polyphase history. The depocentres attain a maximum sediment thickness of more than 5500 m in the Vienna basin and more than 8500 m in the Danube basin (Kilényi and Šefara, 1989). The two basins are separated by the horst structure of the Malé Karpaty Mts., but had a com-

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mon evolution until Middle Miocene times (Kováč et al., 1993a, c).

The Vienna basin is commonly regarded as a typical example of thin-skinned tectonics. Royden (1985) proposed thin-skinned pull-apart extension of the nappe pile as a mechanism for subsidence in the Vienna basin. A 50-km sinistral strike-slip motion has been proposed (Roth, 1980) along the border faults of the basin.

During the last decade a large number of studies have generated a more complete dataset of the Vienna basin (e.g., Tomek and Thon, 1988, Slovakian territory; Wessely, 1988, Austrian territory) and the Danube basin (e.g., Vass et al., 1990). Seismic sections (Wessely, 1988) give evidence for folding and overthrusting of the Egerian–Eggenburgian strata (27–18.5 Ma). Tomek and Thon (1988) demonstrated from seismic interpretations the existence of deep, north-dipping, low-angle normal faults of Pliocene age in the Vienna basin. In the Austrian domain the Steinberg fault and Leopoldsdorf fault extend into the basement. Based on these observations, Wessely (1988) suggested a modification to the interpretation of Royden et al. (1983) with respect to the tectonic level to which extension occurred in the Vienna basin. Recent seismic interpretations (Horváth, 1993) revealed that in the Little Hungarian Plain (Southern Danube basin) preexisting compressional faults were reactivated as low-angle normal faults, leading to tectonic unroofing of the metamorphic basement.

An increase of thermal subsidence with increasing distance from the thrust front has been described (Royden and Dövényi, 1988), which exhibits a trend from thin-skinned (close to the thrust front) to whole lithospheric extension (in the Central Pannonian

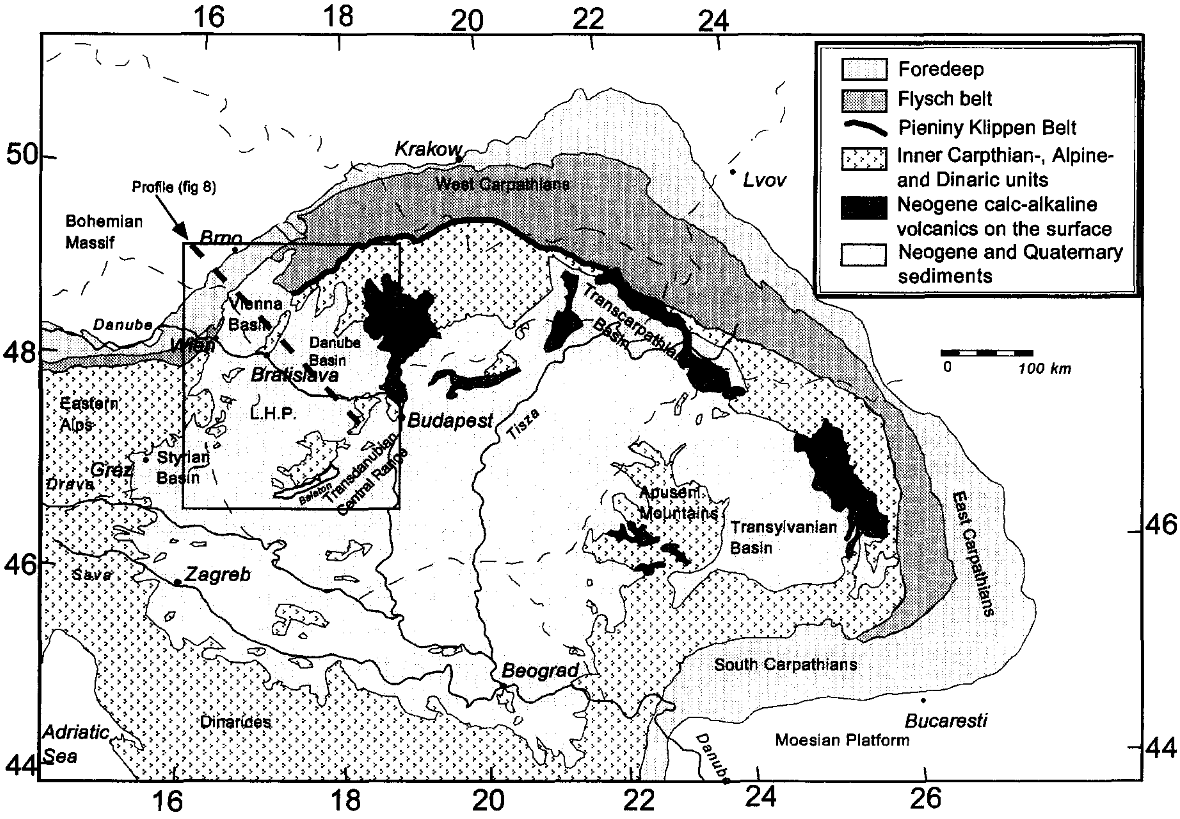

Fig. 1. Map showing the locations of the basins relative to the Carpathian arc and the Pannonian Basin System. Box indicates study area (Fig. 2). Profile shown in Fig. 8. *L.H.P.* = Little Hungarian Plain; *P.K.B* = Pieniny Klippen Belt.

Basin System), but extension in both the Vienna and the Danube basin was considered by these authors to be limited to the upper few tens of kilometres.

As a part of the Pannonian basin, the Danube basin and especially the Vienna basin have been used frequently to test quantitative tectonic models for extensional basin formation, yielding different estimated amounts of extension. Stegena et al. (1975) proposed a model involving subcrustal erosion, yielding 15–20% of extension (Horváth et al., 1975). Sclater et al. (1980) and Royden and Dövényi (1988) applied a modified stretching model (non-uniform stretching model), evoking different amounts of extension in the crust and the lithosphere, where δ is the crustal and β is the lithospheric extension value, producing extension values for the Vienna basin ($\delta = 1.25$, $\beta = 1.00$) and the Danube basin ($\delta = 1.25$ and $\beta = 1.25$–2.0).

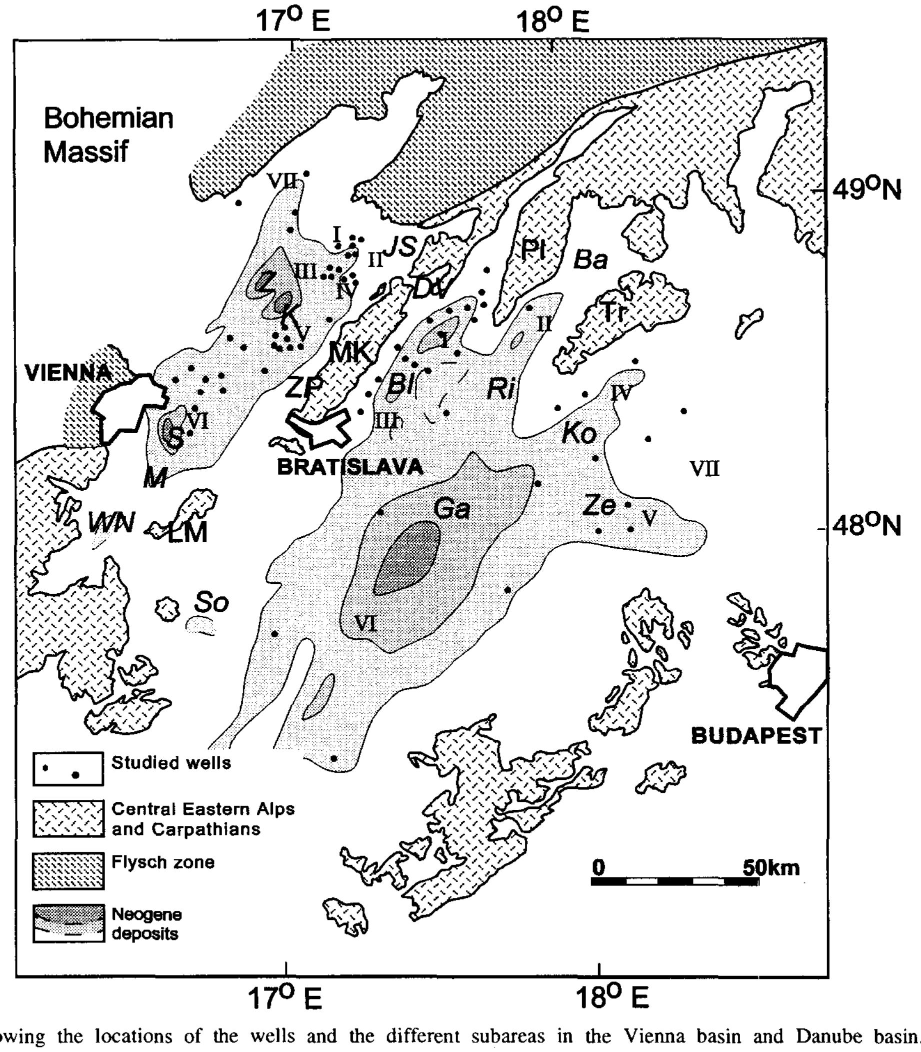

Fig. 2. Map showing the locations of the wells and the different subareas in the Vienna basin and Danube basin. Explanation of abbreviations, Mountain ranges: *MK* = Malé Karpaty Mountains, *PI* = Považský Inovec Mountains, *Tr* = Tribeč Mountains, *LM* = Leitha Mountains; Vienna basin: *WN* = Wiener-Neustadt basin, *M* = Mitterndorfer graben, *S* = Schwechat depression, *Z* = Zisterdorfer depression, *K* = Kúty graben, *JS* = Jablonica Senica depression, *ZP* = Zohor–Plavecký graben; Danube basin: *DV* = Dobrá Voda depression, *Ba* = Bánovce depression, *Bl* = Blatné depression, *Ri* = Rišňovce depression, *Ko* = Komjatice depression, *Ze* = Želiezovce depression, *Ga* = Gabčikovo basin.

Recently new concepts on the formation of the Northern Pannonian basin system and surrounding regions have been proposed, like extrusion tectonics (Ratschbacher et al., 1991) and subduction–delamination (Morley, 1994), which are able to explain extensional basins in an overall compressional setting.

In the following we apply models incorporating lateral heat flow (Pitman and Andrews, 1985) and non-uniform stretching (Royden and Keen, 1980) to the new geological observations to reevaluate the tectonic histories of the basins.

A large number of wells allows us to study the subsidence history in both basins in detail, and to distinguish different tectonic events and their impact on a basin or subbasin scale. Forward modelling is used to quantify the extensional events in terms of crustal extension (δ) and lithospheric extension (β) values. This approach enables us to study the changes in δ/β ratio throughout the basins.

The presented subsidence data are compared with palaeogeographical and palaeostress data to distinguish tectonic events and their impact on basin evolution.

2. Tectonic history

Three major tectonic phases are recognized in the basin evolution, each corresponding to a distinct tectonic regime and palaeostress field orientation. The overall north to south and east to west migration of depocentres (Vass et al., 1988) in these basins during the Neogene illustrates the effects of the changing tectonic setting. This migration is also reflected in the geothermal gradient which is highest along the eastern flanks of the Vienna basin (Král et al., 1985).

The Eggenburgian transgression (22 Ma) advanced from the Alpine foredeep eastwards, crossed the flysch accretionary wedge in the present northern part of the Vienna basin and from here extended along the front of the Central Western Carpathians following the Pieniny Klippen Belt. The northern margin of the W–E-trending Lower Miocene basin consisted of elevated flysch nappes of the Magura Group (Kováč et al., 1989a, b). The southern margin was built up from uplifted Alpine and Central Western Carpathian units forming at present the basement of the southern part of the Vienna basin, Danube basin and the Malé Karpaty Mts. (Kováč et al., 1991; Seifert, 1992). The Lower Miocene sediments overlying the Flysch Zone in the Vienna basin were deposited in a piggy-back basin setting. The sediments overlying the Central Carpathian units were deposited in a wrench–furrow-type basin. The evolution of the whole sedimentary area was controlled by a NW–SE-oriented compressional palaeostress field (Nemčok et al., 1989; Kováč et al., 1989b; Marko et al., 1991; Fodor, 1995).

Important palaeogeographical changes were recorded at the end of the Lower Miocene (17.5 Ma) in the zone between the Eastern Alps, where the overthrust movements stopped (Jiříček, 1979), and the northward advancing Western Carpathians, where the overthrust movements in flysch accretionary wedge were still forced by subduction–collision processes (Tomek and Hall, 1993). The basin geometry was controlled by a N–S-oriented palaeostress field (Nemčok et al., 1989; Vass et al., 1990; Kováč et al., 1993a). A dominant role in the basin evolution was played by the NE–SW-trending sinistral strike-slip faults (Fig. 3), trending along the Malé Karpaty Mountains and the front of the Magura Nappe Group (Roth, 1980).

In the Vienna basin the subsidence accelerated and the basin enlarged to the south during the Lower Miocene. Pelitic and psammitic turbidite sediments of basinal facies reach a maximal thickness of over 2000 m in the north (Špička, 1969; Jiříček and Seifert, 1990). Southwards, they pass into psammitic–pelitic facies coarsening upward, overlain by large alluvial-delta fans of the Aderklaa and Jablonica conglomerates (Kováč, 1986; Wessely, 1988).

In the Danube basin the deposits of Karpathian age are preserved along the western flanks of the basin, in the north of the basin, in the Jablonica and Blatné depressions and in northwestern Hungary, in the Sopron area. Some Karpathian (lower Badenian) deposits are present also along the Rába fault zone, in a narrow zone, covering the pre-Neogene basement of the Little Hungarian Plain (Tari et al., 1992)

The counter-clockwise rotation of the western part of the Carpathians (Túnyi and Kováč, 1991), due to changes of the structural pattern led to changes in the palaeogeography in the Vienna and Danube basins at

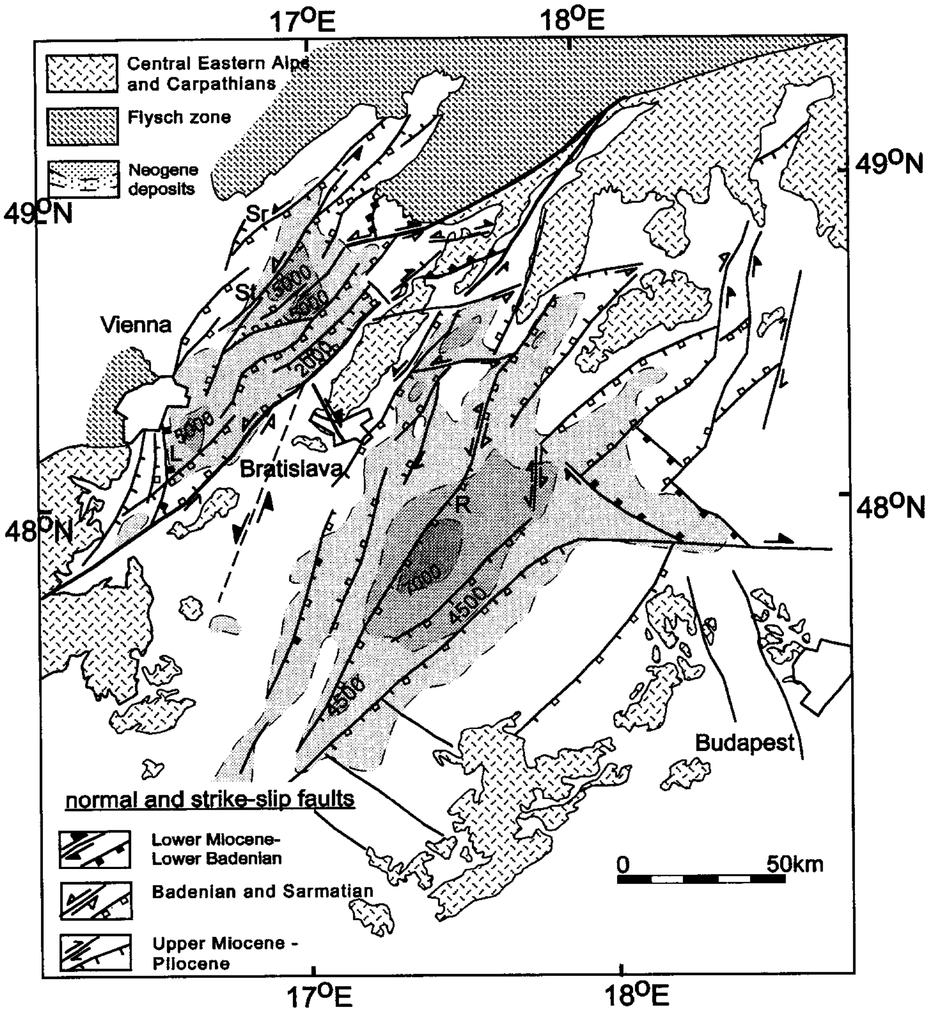

Fig. 3. Tectonic sketch map of the Vienna and Danube basins, illustrating the interactions of the different strike-slip systems and their relations to the individual subbasins. *St:* = Steinberg fault, *Sr* = Schratteberg fault, *R* = Raba fault.

the beginning of the Middle Miocene (16.5 Ma). The early Badenian transgression from the Mediterranean invaded the southern part of the Danube basin (Little Hungarian Plain) and the entire Vienna basin.

The early Badenian evolution of the Vienna basin continued to be controlled by N–S-oriented compression (Nemčok et al., 1989). The lower Badenian deposition represents a separate sedimentary cycle displaying in marginal parts an angular discordance with the Karpathian strata. The steep morphology of the eastern margin documents the coarse clastic fan-deltas, talus cones and debris aprons up to 400 m thick, deposited on the slopes of the Leitha and Malé Karpaty Mts. during the lower and middle Badenian (Vass et al., 1988; Sauer et al., 1992).

In the southern part of the Danube basin (Little Hungarian Plain) the measured palaeostress field documents a NNW–SSE- to NW–SE-oriented compressional field (Vass et al., 1993). This activated the NW–SE-trending normal faults on the northern margin of the lower Badenian Danube basin (Želiezovce depression), where 1200 m of clays, siltstones and sandstones were deposited (Adam and Dlabač, 1969).

In the Middle Miocene, the oblique collision between the North European Platform (Bohemian Massif) and western part of the Carpathians terminated (Jiříček, 1979; Csontos et al., 1992). The movement of the overriding Carpathian plate changed to a northeastward direction, which is documented by the palaeostress field with a NE–SW-oriented principal compression axis (Nemčok et al., 1989; Csontos et al., 1991). The Middle Miocene depocentres of the Vienna and Danube basins opened in a transtensional regime, controlling the ENE–WSW sinistral strike-slip faults and the NE–SW-oriented normal faults (Tari et al., 1992; Kováč et al., 1993c). In this time, the Lower Miocene deposits, situated between the Vienna basin and the northern part of the Danube basin (Jablonica and Dobrá Voda depressions) have been incorporated into the rising Malé Karpaty horst structure (Kováč et al., 1991). In the central parts of the Vienna basin (e.g., Zisterdorf, Gajary and Kúty depressions) the Badenian and Sarmatian pelitic–psammitic deposits reach a maximal thickness of 2500–3000 m (Jiříček and Seifert, 1990).

The middle Badenian marine transgression invaded the northern part of the Danube basin. Rapid subsidence in the Blatné, Rišňovce and Komjatice depressions was followed by deposition of 2000–3000-m-thick pelitic and psammitic sequences during the middle and late Badenian. During the Sarmatian, where the subsidence rapidly decreased, 300–600 m of pelitic–psammitic sediments were deposited (Adam and Dlabač, 1969).

A southward shift of depocentres was determined for the Late Miocene. During this time the central depression of the Danube basin (Gabčíkovo depression) developed. The present depth of this basin exceeds 8500 m (Kilényi and Šefara, 1989). The basins were filled up with sediments transported by rivers from the rising Alpine–Carpathian orogen. In deltaic to lacustrine environments clays and sands were deposited, reaching a thickness up to 1000 m in the Vienna basin and 4000 m in the Danube basin (Adam and Dlabač, 1969; Jiříček and Seifert, 1990; Vass et al., 1990).

During the Pliocene the uplift of the Eastern Alps and Western Carpathians accelerated, leading to erosion of the Miocene deposits in the northern parts of basins. Subsidence in the central and southern part led to further accumulation of river and lake deposits in the Vienna and Danube basins. Prominent examples are the Mitterndorfer and Zohor–Plavecký Mikuláš, grabens in the Vienna basin and the Gabčíkovo depression in the Danube basin, where the Pliocene deposits reach a thickness of up to 1200 m (Gaža, 1984).

3. Subsidence analysis

We have reconstructed the subsidence history of the Vienna and Danube basins by backstripping more than 90 wells using stratigraphic data from Špička (1969), Biela (1978a, b) and Nagymarosy (1981). The backstripping procedure removes the effect of sediment loading and compaction from the basement subsidence, allowing quantification of tectonic basin subsidence (Bond and Kominz, 1984). The amount of decompaction is calculated using empirical porosity/depth relations for the specific lithology of each layer. Local isostatic behaviour of the lithosphere is assumed. The input for this computation is specifying of stratigraphic data: sediment type, age, thickness and lithologic characteristics bearing on porosity/depth relations as well as density for each lithology (cf. Kooi and Cloetingh, 1989; Peper and Cloetingh, 1992). We have not incorporated palaeowater-depth changes in this study since sedimentological data indicate no significant changes in palaeowater-depth. We have also refrained from the incorporation of changes in relative sea level, since both basins have been separated from the world ocean after 10.5 Ma (Steininger et al., 1988).

3.1. The Vienna basin

The Vienna basin consists of a system of horsts and grabens. The uplifted blocks along the western and eastern basin margin are separated from deep depressions by faults with large displacements. The central axis of the basin is marked by an elevated zone with a sigmoidal shape which disappears in the southern part of the basin (Wessely, 1988; Sauer et al., 1992).

Geographically the Vienna basin is subdivided in three parts. The northern part covers the area north of the Kuty graben (Fig. 2). The central part extends from the Kuty graben to the Schwechat depression, including the Zistersdorf depression. The southern-most part of the Vienna basin, which is not included in this study, covers the area south of the Schwechat depression, including the Wiener-Neustadt basin and the Mitterndorfer depression (Fig. 2).

The pre-Neogene basement of the western part of the Vienna basin is built up of the Flysch Zone on top of the accretionary wedge, in front of the palaeoalpine orogen (Eliáš et al., 1990). The nappe pile of the Northern Calcareous Alps, tectonically overlaying the Central Alpine and Central Western Carpathian units, represents the basement of the eastern part of the Vienna basin (Wessely, 1992).

In order to eliminate the influence of movements of individual fault blocks we established seven subareas, based on the locations of the wells in the basin and the overall shape of the subsidence curves (Fig. 2). In the northern part of the Vienna basin, we distinguished between the Štefanov area (I, II) and the area of Studienka (IV). On the eastern side of the basin, built up mainly of units of the Northern Calcareous Alps, we distinguished the Studienka (III) and Malacky (V) areas. Area III is located in the northern part of the Vienna basin and area V represents the northern part of the central Vienna basin. Area VI represents the southern part of the central Vienna basin, located in Austria. The basement of area VII, located on the western flanks of the basin, consists of flysch nappes. The tectonic subsidence patterns for the different wells are depicted in Figs. 4a–4f.

The first sediments deposited in the Vienna basin are of Eggenburgian age (22 Ma). This phase of shallow subsidence lasted until the end of Ottnangian. For Karpathian times (17.5–16.5 Ma) the subsidence curves document a rapid increase of subsidence. With the exception of some wells on the northwestern flanks (Moravian part VII) and on the northeast edge of the Vienna basin (Štefanov area I) all wells display a contemporaneous onset of 300–600 m of tectonic subsidence along the eastern flanks of the basin.

The change from one subsidence mode to the other is more abrupt in areas situated on the eastern margin of the central depression (Studienka III and Malacky V). In the central parts of the basin (areas III, V and VI) subsidence then changes to a more gradually decreasing mode during the next 10 Ma (Fig. 4). The subsidence curve has a concave shape, which is steeper in areas located more to the south.

On the northwestern flanks of the Vienna basin (Moravian/Flysch part VII) a shift of the onset of tectonically controlled subsidence to early Badenian is observed, similarly as found for some wells in the Austrian part of the basin (area VI). For the Badenian a gradually decreasing subsidence mode is observed.

In some of the wells situated in the northeastern part of the Vienna basin (Štefanov area I, Ib, and Studienka II area) a second phase of increased subsidence occurs in the late Badenian–early Sarmatian causing 100–300 m tectonic subsidence between 14.0 and 13.0 Ma.

The third phase of increased subsidence at the end of the Late Miocene and beginning of the Pliocene (7–4 Ma) is recorded in the central part of the Vienna basin and in some wells in the southern part of the basin (Malacky area V and Austrian part VI).

The most important differences in the subsidence history displayed in Fig. 4 occurred after the first phase of subsidence increase. In the northernmost areas, tectonic subsidence abruptly stops at 17 Ma, only to be renewed by the small event at 14–13.5 Ma. In contrast to the subsidence record on the western and eastern flanks of the basin and in its central-southern part, subsidence only slowly decreases after 17 Ma.

The structural and palaeogeographical analyses of the Vienna basin (Jiříček and Tomek, 1981; Royden, 1985; Wessely, 1988; Tomek and Thon, 1988; Jiříček, 1988; Jiříček and Seifert, 1990; Fodor et al., 1990; Kováč et al., 1993c) indicate a major wrenching event which opened the Vienna basin during the Karpathian. NE–SW left-lateral strike slips located in the basement along the eastern margin of the basin played the most important role (Fig. 3). Reactivation of early Badenian faults with the same orientation (Roth, 1980) trending along the western flanks of the basin occurred (Fig. 3). During the Middle Miocene, NE–SW and NNE–SSW normal faults with large displacements played a dominant role.

The wells Lednice (Led) and Josefov (Jo), situated in the Moravian part (Flysch Zone, area VII) of the Vienna basin show a very shallow subsidence, possibly relating to a thin-skinned origin. The wells Břeclav (Br) and Hruška (Hr), in the same area, show a subsidence history very similar to that established for the Austrian part of the basin (area VI). The wells are situated above the Steinberg fault, which penetrates the basement of the basin (Bohemian Massif). A similar situation occurs at the Schrattenberg fault (Wessely, 1988). It is likely that the subsidence was here mainly controlled by platform flexure due to Carpathian nappe pile overthrusting.

The second phase of tectonically controlled subsidence (14–13.5 Ma) is contemporaneous with the sigmoidal bending (sinistral strike slip) of the Klippen Belt in the central part of the Western Carpathians (Kováč and Hók, 1993). Sedimentation in the northwestern part of the basin was controlled by ENE–WSW-trending sinistral strike slip faults and NE–SW normal faults. This caused the opening of the Kovâlov depression in the northern part of the Vienna basin and the widening of the Moravian central depression. The subsidence of this part of the basin was accompanied by a marine transgression to the northernmost regions of the Vienna basin (Jiříček and Seifert, 1990).

The last, Pontian to Pliocene, phase (7–4 Ma) of accelerated subsidence corresponds to the opening of the grabens along the eastern margin of the Vienna basin: the Wiener-Neustadt basin, Mitterndorf and Zohor–Plavecký Mikuláš grabens. They are separated by large faults from the eastern margin—Leitha

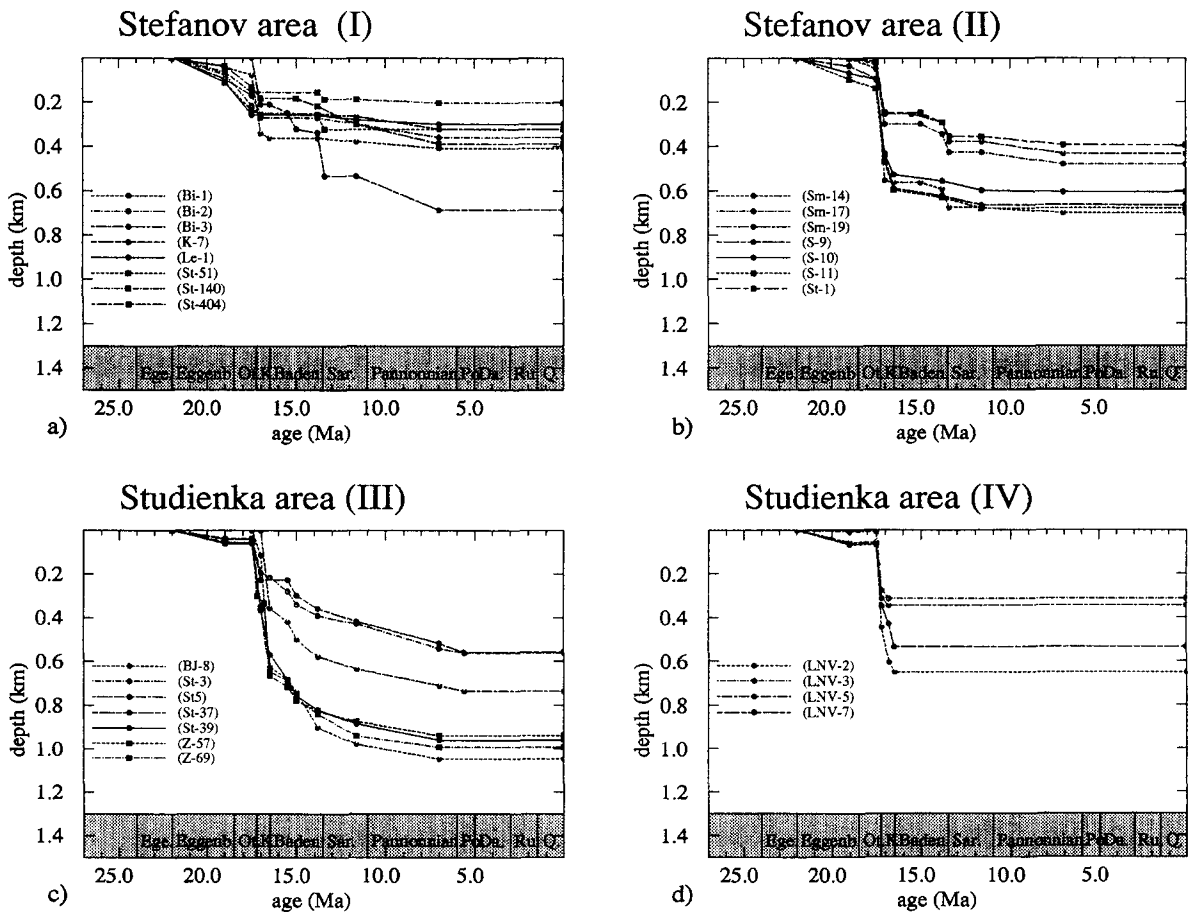

Fig. 4. Diagrams showing the tectonic subsidence history for the different subareas in the Vienna basin. Note the different patterns, coherency inside study areas and coeval onset of warping.

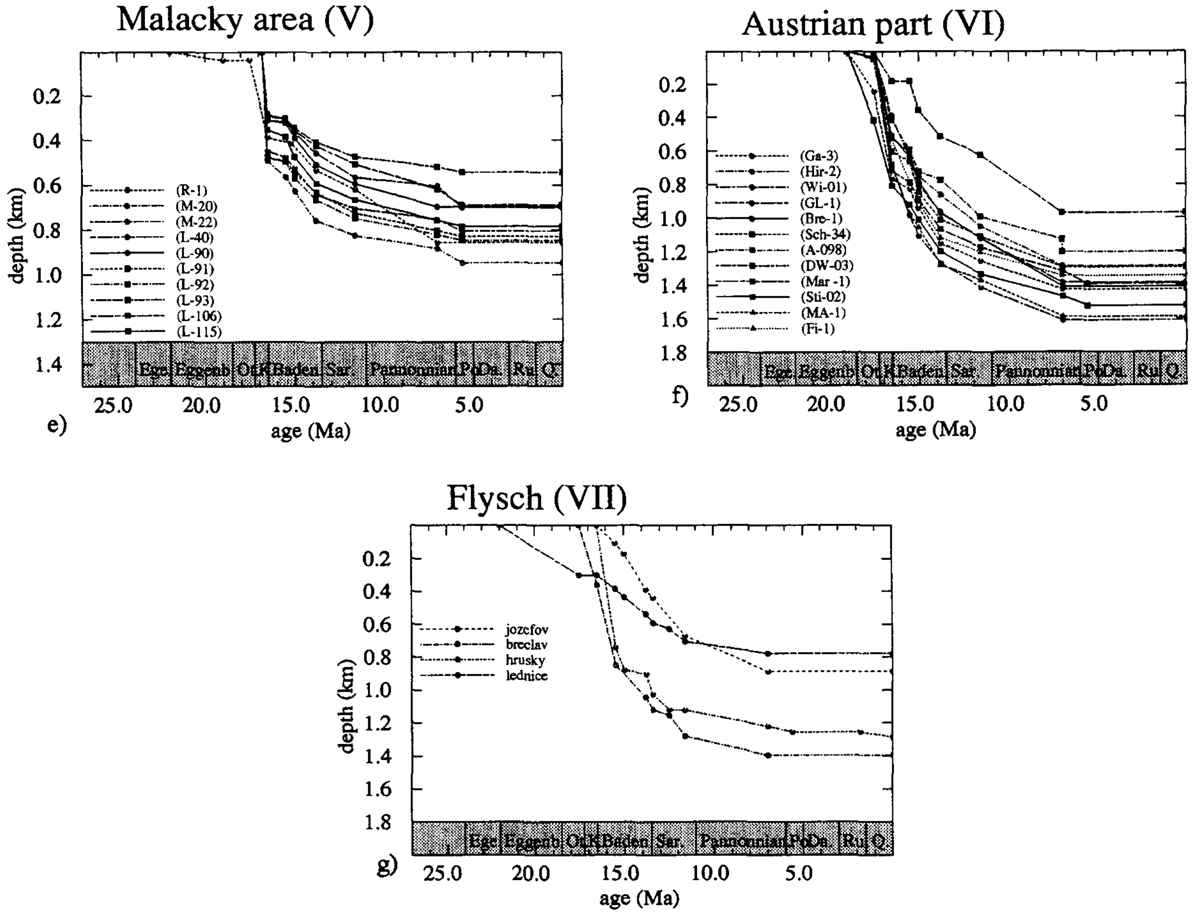

Fig. 4 (continued).

and Malé Karpaty Mts. The documented extension is continuing to the present day, accompanied by seismicity (Gutdeutsch and Aric, 1988).

3.2. The Danube basin (Danube lowland and Little Hungarian Plain)

The Danube basin consists of subbasins (Figs. 2 and 3), e.g., four fingerlike protrusions, from west to east; the Blatné, the Rišňovce, the Komjatice and the Želiezovce depressions and a depression in the central part of the basin (Gabčíkovo depression) (Vass et al., 1990).

The pre-Neogene basement of the Danube basin is formed by the Central Western Carpathian unit in the northern part (Fusán et al., 1987) and the Central Alpine and North Hungarian Pelso units (Fülöp et al., 1987) in the southern part.

The tectonic subsidence patterns for the different wells are depicted in Fig. 5. Based on the locations of the wells in the basin and the shape of the subsidence curves seven sub-areas were distinguished: the Blatné depression (I), Rišňovce depression (II), the western flanks of the Danube basin (III), the Komjatice depression (IV), the Želiezovce depression (V), the Hungarian central and southern parts of the basin (VI) and the area of neovolcanites (VII).

In the Eggenburgian (22 Ma), sedimentation began only in the northwestern part of the Danube basin. This phase of shallow subsidence (area I) lasted until the end of the Ottnangian. Rapid subsidence during the Karpathian (17.5–17 Ma) can be observed in some wells on the western flanks of the basin (Blatné depression and area III). This is followed by a short period without tectonic subsidence until the middle Badenian (15.5 Ma).

During the early Badenian, subsidence begins in the Želiezovce depression (area V) situated on the eastern margin of the Danube basin. The tectonic subsidence is almost restricted to one initial phase with relatively high subsidence rates lasting from 16.5 until 15.5 Ma.

Rapid tectonic subsidence is documented in the Blatné depression (area I) during the middle Badenian (15.5–15 Ma). This is followed by a period of gradual slow to zero tectonic subsidence until the last, less pronounced, phase of increased subsidence at about 7–4 Ma.

In the central part of the Danube basin the second phase of increased subsidence lasts from 15.5 until 14 Ma, followed by a period of gradual subsidence. A last phase of rapid subsidence occurs again from about 7 until 4 Ma, recorded in most of the subsidence curves for this area.

At 15.5 Ma the subsidence in the Rišňovce and Komjatice depressions (areas II and IV) starts. These areas show a general decreasing trend in subsidence starting in the middle Badenian. Similarly to other areas at about 7–4 Ma a phase of increased tectonic subsidence is observed.

The last phase of enhanced subsidence lasting

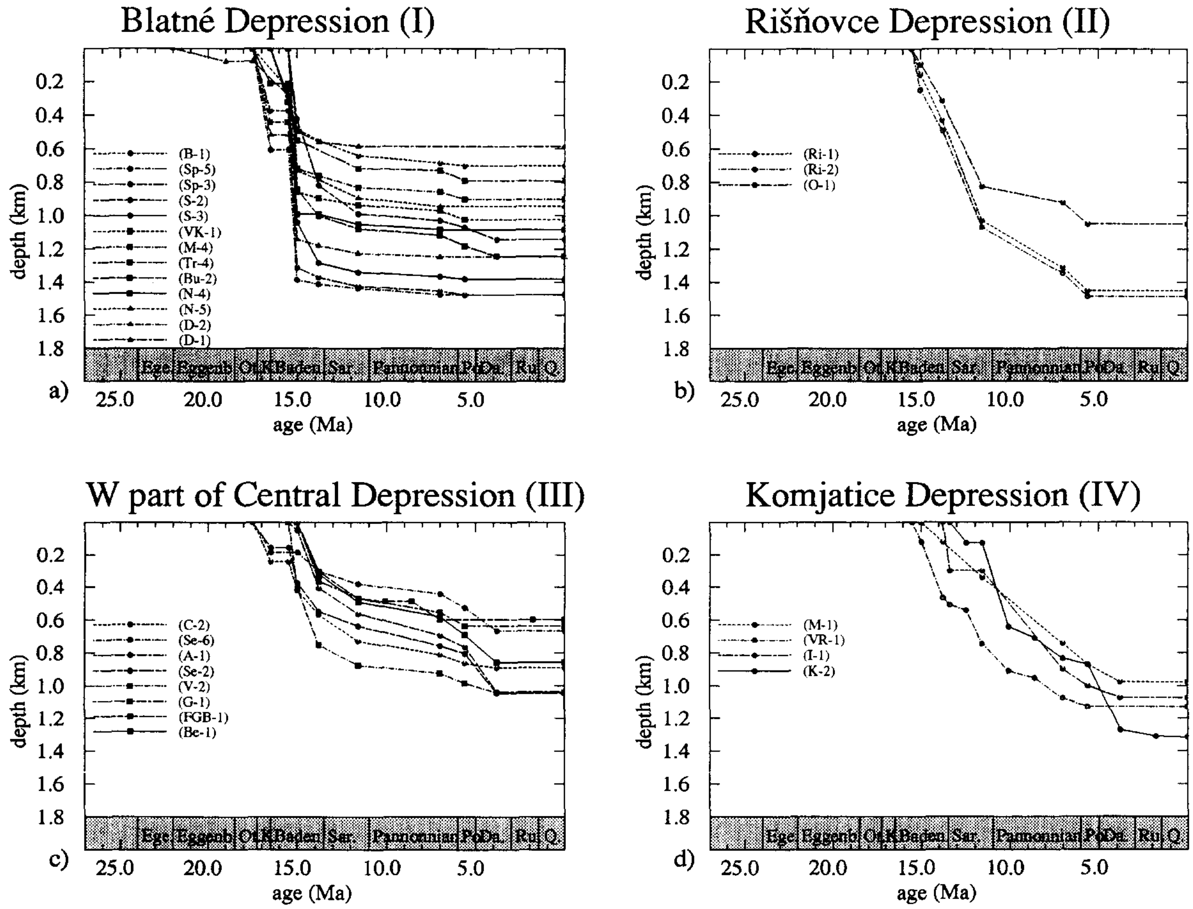

Fig. 5. Diagrams showing the tectonic subsidence history for the different subareas in the Danube basin.

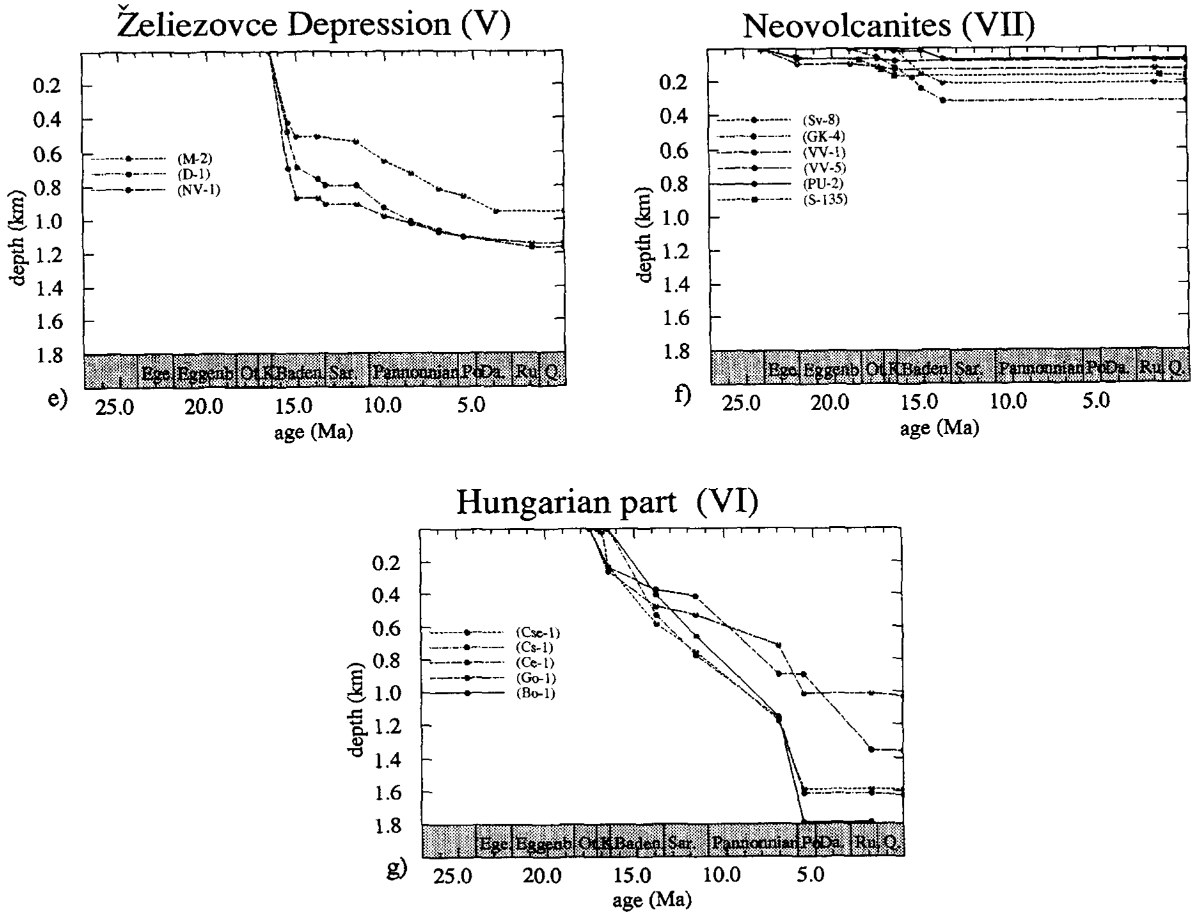

Fig. 5 (continued).

from the Late Miocene until the Pliocene (7–4 Ma) culminated during the Pontian. This phase is connected with the subsidence of the central part of the Danube basin, suggesting a tectonic control.

4. Interpretation

The structural and palaeogeographical analyses document a common evolution of the present Vienna basin, northern part of the Malé Karpaty Mts., northwestern part of the Danube basin (Blatné depression) and the eastward-situated Bánovce depression during the Early Miocene (Kováč et al., 1989a, 1991, 1993a, b; Nemčok et al., 1989; Marko et al., 1990, 1991; Fodor et al., 1990).

Opening of the Eggenburgian basins was controlled by ENE–WSW-trending dextral strike-slip faults and NW–SE normal faults associated with N–S sinistral strike slip faults and NE–SW-trending back thrusts. The transpressive regime, with a NW–SE-oriented main compression axis, is mirrored in the small size of basins and slow subsidence as documented by the backstripping analysis (Fig. 5).

The northwards escape of the Central Western Carpathians during the Karpathian indicate a major wrenching event which opened the Vienna basin. This event, characterised by a palaeostress field with N–S-oriented main compression was recognised also in the northwestern part and western flanks of the Danube basin. The most important role is played by NE–SW left-lateral strike-slip faults in the basement along the western margin of the basin. Right-stepping faults caused gradual closing of the Dobrá Voda and Jablonica depressions (at present belonging to the northern part of the Malé Karpaty horst structure). Left-stepping faults opened the Blatné depression (Fig. 3).

The oblique collision of the Western Carpathians was accompanied by a counter-clockwise rotation during the early Badenian (Túnyi and Kováč, 1991). During this phase, an interruption of deposition in the northwestern part of the basin (Blatné depression) occurs. In the more southward-situated Želiezovce depression, however, the tectonic subsidence is restricted to this phase with relatively high subsidence rates. The sedimentation was affected by a NNE–SSW- to NE–SW-oriented compression (Vass et al., 1993). A dominant role was played by the NW–SE- to NNE–SSW-running normal faults. Activation of N–S to NNE–SSW sinistral strike-slip faults and WSW–ENE dextral strike-slip faults can not be excluded (Kováč and Hók, 1993).

Following the eastward migration of the Alpine–Carpathian collision with the North European plate during the Miocene, associated with migration of the last overthrusting along the Carpathian front (Jiříček, 1979) a rotation of the palaeostress field is observed in the Central Western Carpathians during the Miocene. From the middle Badenian onward, sedimentation in the depocentres of the northern parts of the Danube basin was affected by a palaeostress field with a NE–SW-oriented main compression (Nemčok et al., 1989; Csontos et al., 1991; Nemčok, 1993; Vass et al., 1993). In the Blatné depression, ENE–WSW sinistral strike-slips developed, and the earlier NE–SW-oriented faults were reactivated as normal faults, similar to the Vienna basin (Marko et al., 1991; Kováč et al., 1993a). The difference between the rapid subsidence in the Blatné depression and a long period (10 Ma) of slowly increasing subsidence in the Rišňovce and Komjatice depressions from the middle Badenian to Pannonian can be explained by a preferred activation of normal faults in the last two depressions. A similar, preferential activation of NE–SW normal (listric) faults (Pěničková and Dvořáková, 1985; Tari et al., 1992; Vass et al., 1993) is suggested by the results of the backstripping analysis of the western flanks, Hungarian central and southern part of Danube basin during the Middle and Late Miocene (Fig. 5). Apart from this phase which affected the entire basin, the last phase of increased subsidence (7–4 Ma) is more pronounced in the Hungarian part, suggesting a tectonically controlled acceleration of subsidence during the Pontian, even during the Pliocene.

Recent results of deep seismic investigations of the Danube basin (Hrušecký et al., 1993) document a NNE–SSW-trending strike-slip fault zone in the central, Gabčikovo depression with a negative flower structure in the Sarmatian and Pannonian sediments. The backstripping analysis presented above, shows an active phase of tectonic subsidence in the nearest situated well Kolárovo K-2 (area IV) for the Sarmatian/Pannonian and Pontian/Pliocene boundaries.

The subsidence patterns of the Blatné depression (area I) and the Želiezovce depression (area V) are remarkably different from the other subbasins. In this respect they show distinct phases of increased subsidence, followed by periods of relatively slow subsidence. In contrast in the Rišňovce and Komjatice depressions (areas II and IV), as well as in the Hungarian central and southern parts of the Danube basin (area VII), the gradually decreasing subsidence trend is the most prominent feature.

According to the pure-shear stretching model (McKenzie, 1978), the rapid increase of subsidence can be explained in terms of extensional phases, whereas the gradual decreasing subsidence is attributed to thermal subsidence. The subsidence pattern is consistent with asymmetrical subsidence (Wernicke, 1985) along a large-scale SE-dipping fault system along the western margin of the Danube basin (Fusán et al., 1987; Dank and Fülöp, 1990; Tari et al., 1992). Asymmetrical extension along this fault system explains the absence of a thermal phase in the Blatné depression and the absence of an initial phase in the eastward-situated Rišňovce, Komjatice and Gabčíkovo central depressions. The western part of the basin (area III) forms an intermediate area, with both initial and thermal subsidence.

5. Forward models

In the following section we present the results of forward modelling of basin subsidence. Adopting a modified McKenzie stretching model, incorporating the effects of laterally changing stretching parameters. We developed for the Vienna and the Danube basins a first-order model, to test our hypotheses on the basin evolution and underlying lithosphere. Calculated subsidence curves for varying crustal and subcrustal stretching and different basin geometries (basin width, thickness of the crust and lithosphere) are compared with the subsidence histories reconstructed from backstripping analysis.

5.1. Vienna basin

The subsidence patterns derived from backstripping in the Vienna basin demonstrate a trend of increasing thermal subsidence in a southward direction. Throughout the entire basin an initial subsidence phase can be observed. Fig. 6a shows a comparison of the observed subsidence and the subsidence predicted by the forward model. For the northern part of the Vienna basin (areas I and II) a model with δ (crustal extension factor) from 1.04 (4% extension) to 1.10 (10% extension) and β (subcrustal extension) of 1.0 (no subcrustal extension) produced the curve of Fig. 6a. The $1.04 \geq \delta \geq 1.05$ is an average for extension in the entire 30-km-thick crust. Seismic profiles and structural interpretation (Tomek and Thon, 1988; Wessely, 1988; Čekan et al., 1990; Hamilton et al., 1990) suggest that extension only occurred in the uppermost 4 km of the crust (thin-skinned extension). Limiting the extension to the upper 4 km of the crust implies that the extension factor for this part of the crust should be much larger in order to produce the same amount of subsidence.

For the central and southern part (area VI), a model of whole lithospheric extension has been adopted, in order to explain the large amount of thermal subsidence and the initial 700 m of tectonic subsidence. This is consistent with Wessely's suggestion that extension in this part of the Vienna basin is not restricted to the allochthonous thrust sheet, but extends into the autochthonous basement.

We developed a model with a relatively narrow basin (30 km) adopting β (subcrustal extension) between 1.4 and 1.6 and δ (crustal extension) of 1.2 to 1.3. This geometry allows a rapid (20 Ma) equilibration of the thermal anomaly induced by lithospheric stretching due to high lateral heat flow. This

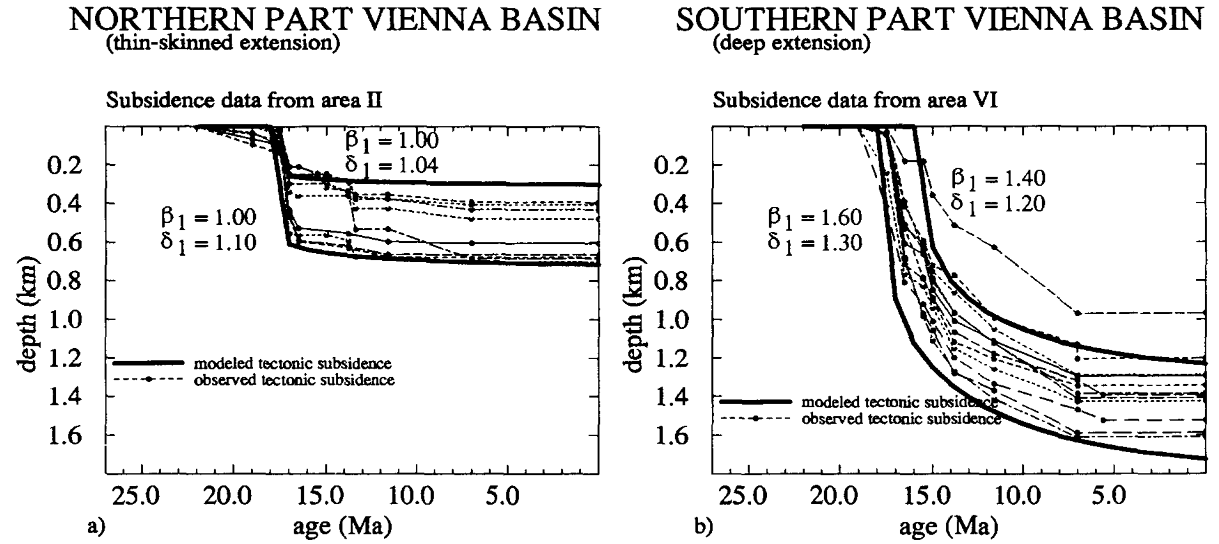

Fig. 6. Thin-skinned versus whole lithospheric extension in the Vienna basin. Comparison between subsidence trends in the northern and southern part of the basin and results from forward modelling. (a) Comparison between observed subsidence in area II and subsidence history derived from forward modelling of a thin-skinned model. (b) Comparison between observed subsidence in area VI and subsidence history derived from forward modelling of a whole lithospheric extension model.

produces the pattern of gradually decreasing post rift subsidence. The subsidence patterns predicted by this model are compared to the observed subsidence pattern in Fig. 6b. Geological data and seismic profiles (Wessely, 1988; Tomek and Thon, 1988; Rumpler and Horváth, 1988) support the geometry of this model.

It should be noted that the numbers presented here are the result of a simple 2-dimensional model. Therefore the trend and not the exact magnitude of extension is of prime importance here. The modelling suggests for the Vienna basin a transition from thin-skinned extension in the northeastern part to whole lithospheric extension in the central and southern parts.

The youngest extension phase (7.0–4.0 Ma) in the Vienna basin has not been incorporated in our modelling. This does, however, not affect the predicted evolution before 7.0 Ma.

A model invoking thin-skinned extension predicts subsidence curves (Fig. 6a) which are consistent with the data in areas II and IV. The modelled extension values are in relative accordance with values obtained by Royden and Dövényi (1988) for the Vienna basin as a whole ($\delta = 1.25$ and $\beta = 1.00$)

5.2. Danube basin

Fig. 7 shows the results of the modelling of the Danube basin. The model for the Blatné depression is based on two crustal extension phases, starting at respectively 18 Ma and 16 Ma and both lasting for 1 Ma. We attributed a crustal extension factor (δ) of 1.10 to the first and 1.14 to the second extension phase in order to obtain the best fit to the maximum observed subsidence in this area. Here also an initial crustal thickness of 30 km was adopted. The subcrustal extension factor was taken to be 1.00.

For the Rišňovce depression we adopt a subcrustal extension phase, with a β between 1.4 and 1.6. The extension phase starts at 15 Ma and lasts for 1 Ma. The crustal extension factor (δ) for both extension phases is estimated between 1.15 and 1.3.

Both models produce a good fit to the observed subsidence histories and support the existence of thin-skinned extension in the northern part of the Vienna basin and the Blatné depression and whole lithospheric extension in the southern parts of both basins. It should be noted that the models do not account for flexural–isostatical responses of the lithosphere and only a relatively simple basin geome-

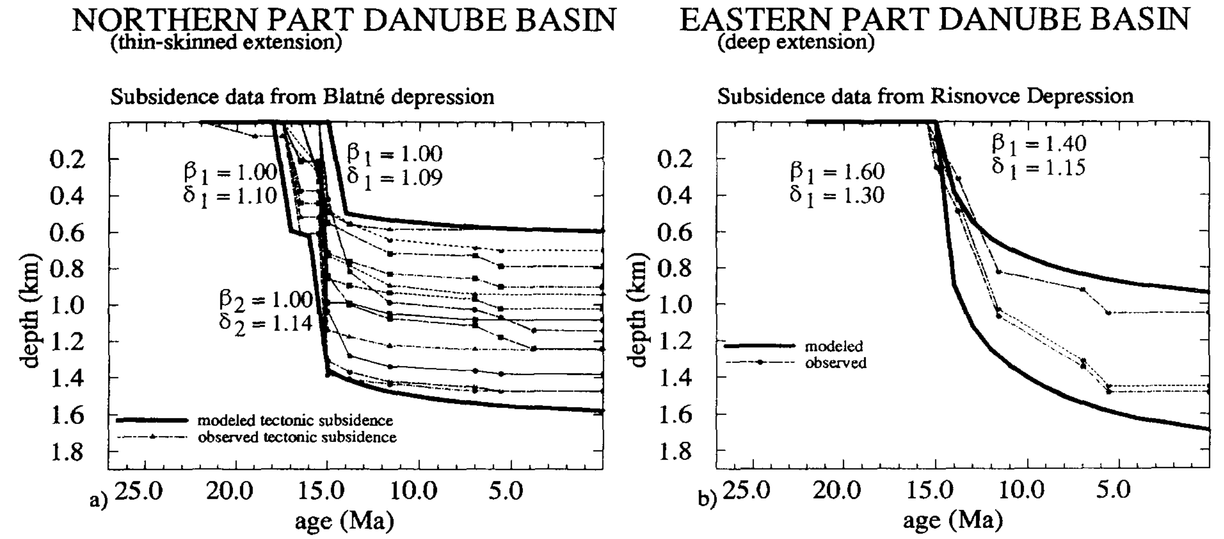

Fig. 7. Thin-skinned versus whole-lithospheric extension in the Danube basin. Comparison between subsidence trends in two parts of the basin and results derived from forward modelling. (a) Comparison between tectonic subsidence in the Blatné depression and results from forward modelling of a thin-skinned plate, using two subsequent stretching phases with a crustal extension factor δ and a no-subcrustal extension ($\beta = 1.00$). (b) Comparison between tectonic subsidence in the eastern (Risnovce) part of the Danube basin and results derived from forward modelling of extension, with β (subcrustal extension) between 1.4 and 1.6 and δ (crustal extension) between 1.15 and 1.30.

try has been used. The β and δ factors are first-order indications for the amount of extension. High-quality seismic data are required to provide better constraints on the basin-geometry and the stratigraphic infill necessary for the construction of a model incorporating flexure and finite strength of the lithosphere during extension (Kusznir and Egar, 1989; Kooi et al., 1992; Janssen et al., 1993; Van der Beek et al., 1994; Van Balen et al., 1995).

The crustal extension values are is good agreement with the estimates obtained by Royden and Dövényi (1988) for crustal extension in the western Danube basin (1.23) and the central and eastern Danube basin (2.08–1.75). However, the concept of non-uniform stretching and especially the important role of subcrustal stretching for the Danube basin was not taken into account in this previous study.

6. Discussion and conclusions

The subsidence curves for the Vienna and Danube basins exhibit differences inside the specified areas due to small-scale block movement superimposed on a large-scale trend of different behaviour of the lithosphere. The block movements creating the graben and horst structures of the Vienna and Danube basins basement (Pěničková and Dvořáková, 1985; Hamilton et al., 1990) do not obscure the general subsidence trends. The timing of the main subsidence phases in both the Vienna and the Danube basins are remarkably similar.

The Early Miocene sedimentation started in a transpressive regime with N–S compression, and NW–SE compression documented in front of the western part of the Carpathians (Nemčok et al., 1989), due to Miocene rotation (Túnyi and Kováč, 1991).

The first, Karpathian extensional phase (17.5–16.5 Ma) in the Vienna basin and along the western margin of the Danube basin coincides with the end of the oblique collision between the Bohemian Massif and the overriding Carpathians. It is marked by the last overthrust movements in the western part of the Western Carpathians loop (Jiříček, 1979) followed by the evolution of the foredeep along the whole Western Carpathian front (Oszczypko and Slaczka, 1989). This phase opened the grabens (pull-apart) with depocentres in the northern part of the present Vienna basin and in the Blatné depression following the zone of tectonic escape of the Carpathian lithospheric fragment. The principal displacement zone was along the Malé Karpaty Mts. as shown by geophysical data (Fusán et al., 1979).

Detachment of the subducting slab (Tomek and Hall, 1993) was followed by mantle upheaval and partial melting of crust, documented by the Miocene volcanic activity (Lexa et al., 1993) in the Western Carpathian hinterland. Mantle upheaval coincides with the second extensional phase (15.5–15.0 Ma) of tectonic subsidence, recorded in the northwestern (Blatné) part of the Danube basin and the onset of gradually decreasing subsidence in the Vienna and the central and southern parts of the Danube basin.

The tectonic subsidence in the northeastern part of the Vienna basin during the late Badenian–Sarmatian (14.0–13.5 Ma) can be considered as migration of subsidence to an external zone of mantle upheaval. During this time the last overthrust movements took place in the eastern part of the Western Carpathian front (Jiříček, 1988) associated with the large subsidence in the eastern part of the foredeep during the early Sarmatian (Oszczypko and Slaczka, 1989).

The last extensional phase (7–4 Ma), which can not be observed in all wells, can be related to thermal collapse associated with uplift of the orogen and accelerated subsidence in the Pannonian basin (Royden et al., 1983; Becker, 1993). An alternative explanation invokes the evolution of a secondary sag basin not superimposed on the other grabens in the Wernicke model (1985) of heterogeneous stretching.

In the northernmost areas of both basins the observed subsidence patterns reflect a shallow extension mechanism that can be interpreted as a thin-skinned pull-apart basin origin. For the southern part of the Vienna basin thin-skinned tectonics alone can not easily explain the observed subsidence pattern. Our forward modelling indicates that lithospheric extension and post rift subsidence due to cooling of the extended lithosphere is a very plausible mechanism to explain the concave shape of the subsidence curves in the southern parts (Figs. 6b and 7b).

Royden (1985) proposed thin-skinned pull apart extension of the nappe pile as a mechanism for subsidence of the Vienna basin, regarded as a typical example of thin-skinned tectonics. Based on the observation that some of the faults (e.g., Steinberg, Leopoldsdorf fault) extend into the basement Wessely (1988) already suggested a modification of this interpretation with respect to the tectonic level to which extension occurred.

$^3He/^4He$ ratio's measured in geothermal waters from northwestern Hungary indicate a substantial component of mantle-derived helium (Deák et al., 1988), indicating mantle involvement and a conduit to the mantle.

Our modelling results on the depth of extension in the Vienna basin partly agree with Royden and Dövényi (1988), confirming their observation of an increase in the depth of extension away from the Carpathian thrust front. In contrast to their findings our analysis demonstrates the existence of whole lithospheric extension in the Vienna and Danube basins.

Heat-flow values predicted for our values of lithospheric extension are in good agreement with the observed heat-flow of 65 mW/m^2 (Vienna basin) and 80 mW/m^2 (Danube basin) (Král et al., 1985).

Subduction-zone roll back (Royden et al., 1983) is regarded as one of the driving mechanisms for extensional basins in the overall compressional setting of the Carpathians. This mechanism produces different overall amounts of extension in the lithosphere with respect to the crust. The existence of large-scale detachment zones (Tomek and Hall, 1993; Tomek, 1993; Fig. 8) underneath the Vienna basin also points towards a non-uniform extension model (Royden and Keen, 1980).

A subduction–delamination model has been proposed for this region (Morley, 1994) explaining the difference in crustal and subcrustal extension, but a migration of extension towards the foreland, which is commonly associated with this model, has not been observed.

Our subsidence analysis supports a non-uniform extension model (Wernicke, 1985) for the Vienna and Danube basins, where a decoupling exists be-

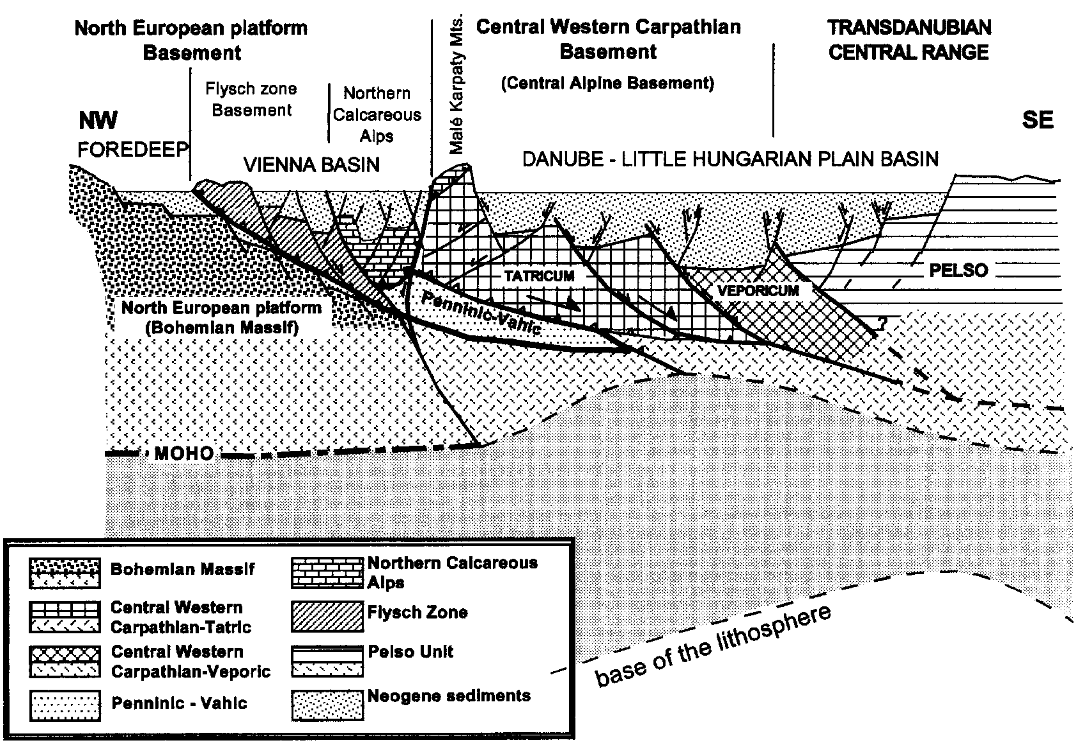

Fig. 8. Idealized sketch of cross-section through the Carpathians and the related basins, partly based on deep seismics (Tomek, 1993), for location see Fig 1. Approximate lenght of profile 250 km.

tween lithospheric and crustal extension. The extension is (at least in the upper part) accommodated along strike-slip faults. A mechanism of reactivation of older faults (Tari et al., 1992) accommodates the rotating stress field (Nemčok et al., 1989; Csontos et al., 1991).

For the Danube basin evolution, a similar process is expected, with an east-dipping listric fault below the Danube basin and minor faults branching of to the surface creating the individual subbasins. A similar model has been proposed for the Pannonian basin (Györfy, 1992).

Taking into consideration the Moho depth, thickness of the lithosphere, heat flow and thickness of Miocene deposits in the Vienna and Danube basins (Babuška et al., 1987; Meissner and Stegena, 1988; Dövényi and Horváth, 1988; Jiříček and Seifert, 1990; Becker, 1993), the low-angle extensional fault model appears to be capable to explain the Vienna and Danube basin evolution.

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References

Adam, Z. and Dlabač, M., 1969. Analysis of thickness and lithofacial evolution of the Danube Basin. Zbor. Geol. Geol. Carpath., 11: 156–171 (in Czech).

Babuška, V., Plomerová, J. and Šilený, J., 1987. Structural model for the subcrustal lithosphere in central Europe. In: K. Fuchs and C. Froideveaux (Editors), Composition, Structure and Dynamics of the Lithosphere–Asthenosphere System. Am. geophys. Union, Geodyn. Ser., 16: 239–251.

Becker, A., 1993. Contemporary stage of stress and neotectonic deformation in the Carpathian and Pannonian region. Terra Nova, 5: 375–388.

Biela, A., 1978a. Deep boreholes in covered areas of the Western Carpathians. Regionálna geológia Záp. Karpát. GUDŠ Bratislava, 10, Part I, 222 pp. (in Slovak).

Biela, A., 1978b. Deep boreholes in covered areas of the Western Carpathians. Regionálna geológia Záp. Karpát. GUDŠ Bratislava, 10, Part II, 224 pp. (in Slovak).

Bond, G. and Kominz, M.A., 1984. Construction of tectonic subsidence curves for the Early Palaeozoic miogeocline, southern Canadian Rocky Mountains: implications for subsidence mechanisms, age of break up, and crustal thinning. Geol. Soc. Am. Bull., 95: 155–173.

Čekan, V., Kocák, A., Tomek, Č., Wessely, G. and Zych, D., 1990. Czechoslovak–Austrian cooperation in geophysical structural exploration in the Vienna Basin. In: D. Minaříkova and H. Lobitzer (Editors), Thirty Years of Geological Cooperation between Austria and Czechoslovakia. Geological Survey, Prague, pp. 23–31.

Csontos, L., Tari, G., Bergerat, F. and Fodor, L., 1991. Evolution of the stress fields in the Carpatho-Pannonian area during the Neogene. Tectonophysics, 199: 73–91.

Csontos, L., Nagymarosy, A., Horváth, F. and Kováč, M., 1992. Tertiary evolution of the Intra-Carpathian area: a model. Tectonophysics, 208: 221–241.

Dank, V. and Fülöp, J., 1990. Map of the pre-Tertiary basement of Hungary. Geol. Survey Budapest.

Deák, J., Horváth, F., Martel, D.J., O'Nions, R.K., Oxburg, E.R. and Stegena, L., 1988. Helium isotopes in geothermal waters from Northwest Hungary. In: L.H. Royden and F. Horváth, F. (Editors), The Pannonian Basin, a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 293–296.

Dövényi, P. and Horváth, F., 1988. A review of temperature, thermal conductivity and heatflow data for the Pannonian basin. In: L.H. Royden and F. Horváth, F. (Editors), The Pannonian Basin, a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 195–233.

Eliáš, M., Schnabel, W. and Stránik, Z., 1990. Comparison of the Flysch Zone of the Eastern Alps and the Western Carpathians based on recent observations. In: D. Minaříkov and H. Lobitzer (Editors), Thirty Years of Geological Cooperation Between Austria and Czechoslovakia. Geological Survey, Prague, pp. 37–46.

Fodor, L., 1995. From transpression to transtension: Oligocene–Miocene structural evolution of the Vienna basin and the East Alpine–Western Carpathian Junction. Tectonophysics, 242: 151–182.

Fodor, L., Marko, F. and Nemčok, M., 1990. Evolution microtectonique et paleo-champs de contraintes du Bassin de Vienne. Geodin. Acta, 4: 147–158.

Fülöp, J., Bresznyánszky, K and Haas, J., 1987. The new map of basin basement of Hungary. Acta Geol. Hung., Budapest, 30: 3–20.

Fusán, O., Ibrmajer, J., and Plančár, J., 1979. Neotectonic blocks of the West Carpathians. Geodynamical Investigations. VEDA, Slov. Acad. Sci., Bratislava, pp. 178–181.

Fusán, O., Biely, A., Ibrmajer, J., Plančár, J. and Rozložník, L., 1987. Basement of the Tertiary of the Inner West Carpathians. GÚDŠ Bratislava, 103 pp.

Gaža, B., 1984. In: J., Bednaříkova and A. Thona (Editors), Hydrocarbon Exploration in Czechoslovakia. Knihovnička Zemního plynu a nafty, 5, Hodonín, pp. 290–298.

Gutdeutsch, R. and Aric, K., 1988. Seismicity and neotectonic of the east Alpine–Carpathian area. In: L.H. Royden and F. Horváth, F. (Editors), The Pannonian Basin, a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 183–195.

Györfy, I., 1992. The simple shear extensional model of the Pannonian basin. Terra Abstracts, Suppl. 2, 4, ALCAPA, Graz, p. 26.

Hamilton, W., Jiříček, R. and Wessely, G., 1990. The Alpine–Carpathian Floor of the Vienna Basin. In: D. Minaříková and H. Lobitzer (Editors), Thirty Years of Geological Cooperation Between Austria and Czechoslovakia. Geological Survey, Prague, pp. 46–55.

Horváth, F., 1993. Towards a mechanical model for the formation of the Pannonian Basin. Tectonophysics, 226: 333–358.

Horváth, F., Stegena, L. and Géczy, B., 1975. Ensimatic and ensialic interarc basins. J. Geophys. Res., 80: 281–283.

Hrušecký, I., Pereszényi, M., Hók, J., Šefara, J. and Vass, D., 1993. The Danube Basin geological pattern in the light of new and reinterpretation of old geophysical data. In: M. Rakús and J. Vozár (Editors), Geodynamický model a hlbinná stavba Západných Karpát. GÚDŠ Bratislava, pp. 291–296.

Janssen, M.E., Torne, S., Cloetingh, S. and Banda, E., 1993. Pliocene uplift of the eastern Iberian margin: inferences from quantitative modelling of the Valencia Through. Earth Plan. Sci. Lett., 119: 585–597.

Jiříček, R., 1979. Structural evolution of the Carpathian arc during the Oligocene and Neogene. In: M. Mahel (Editor), Tectonic Profiles Through the West Carpathians. GÚDŠ Bratislava, pp. 205–215 (in Czech).

Jiříček, R., 1988. Stratigraphy, paleogeography and thickness of the Neogene sediments in the Vienna Basin. Zem. plyn a nafta, 33, 4, Hodonín, pp. 583–662 (in Czech).

Jiříček, R. and Seifert, P., 1990. Paleogeography of the Neogene in the Vienna Basin and the adjacent part of the foredeep. In: D. Minaříková and H. Lobitzer (Editors), Thirty Years of Geological Cooperation Between Austria and Czechoslovakia. Geological Survey, Prague, pp. 89–105.

Jiříček, R. and Tomek, Č., 1981. Sedimentary and structural evolution of the Vienna Basin. Earth Evolut. Sci., 3–4: 195–204.

Kilényi, E. and Šefara, J. (Editors), 1989. Pre-Tertiary Basement Contour Map of the Carpathian Basin Beneath Austria, Czechoslovakia and Hungary. Eotvos Lóránd Geophysical Institute, Budapest, Hungary.

Kooi, H. and Cloetingh, S., 1989. Intraplate stresses and the tectono-stratigraphic evolution of the Central North Sea. Am. Assoc. Pet. Geol. Mem., 46: 541–558.

Kooi, H., Cloetingh, S. and Burrus, J., 1992. Lithospheric necking and regional isostasy at extensional basins, 1. Subsidence and gravity modelling with an application to the Gulf of Lions Margin (SE France). J. Geophys. Res., 97: 17553–17572.

Kováč, M., 1986. Lower Miocene sedimentation in the area of Jablonica depression—a model bound to oblique slip mobile zone. Geol. Carpath., 37: 3–15.

Kováč, M., Cícha, I., Krystek, I., Slaczka, A., Stránik, Z., Oszczypko, N. and Vass, D., 1989a. Palinspastic Maps of the Western Carpathian Neogene. Geological Survey, Prague, 35 pp.

Kováč, M., Baráth, I., Holický, I., Marko F. and Túnyi, I., 1989b. Basin opening in the Lower Miocene strike-slip zone in the SW part of the Western Carpathians. Geol. Carpath., 40: 37–62.

Kováč, M., Michalík, J., Plašienka, D. and Putiš, M., 1991. Malé Karpaty Mts. Geology of the Alpine–Carpathian Junction. Excursion Guide, Bratislava, pp. 61–74.

Kováč, M., Marko, F. and Nemčok, M., 1993a. Neogene structural evolution and basin opening in the Western Carpathians. Geophys. Trans., 37: 297–309.

Kováč, M., Nagy, A. and Baráth, I., 1993b. Ruskovce Fm.—deposits of sediment gravity flows. Miner. Slov. Bratislava, 25: 177–124 (English summ.).

Kováč, M., Nagymarosy A., Soták, J. and Šutovská, K., 1993c. Late Tertiary paleogeographic evolution of the Western Carpathians. Tectonophysics, 226: 401–417.

Kováč, P. and Hók, J., 1993. The Central Slovak Fault System—the field evidence of strike slip. Geol. Carpath., 44: 155–159.

Král, M., Lizoň, I. and Jančí, J., 1985. Geothermal research of the Slovak Republic. Manuscript, GÚDŠ Bratislava.

Kusznir, N.J. and Egar, S.S., 1989. Simple-shear and pure shear models of extensional sedimentary basin formation: application to the Jeanne d' Arc Basin, Grand Banks, Newfoundland. Am. Assoc. Pet. Geol. Mem., 46: 305–322.

Lexa, J., Konečný, V., Kalinčiak, M. and Hojstričová, V., 1993. Distribution of the Carpathian–Pannonian region volcanites in space and time. In: M. Rakús and J. Vozár (Editors), Geodynamický model a hlbinná stavba Západných Karpát. GÚDŠ Bratislava, pp. 57–71 (in Slovak).

Marko, F., Kováč, M., Fodor, L. and Šutovská, K., 1990. Deformation and kinematics of the northern part of the Malé Karpaty Mts. Miocene shear zone. Miner. Slov. Bratislava, 22: 399–410 (in Slovak).

Marko, F., Fodor, L. and Kováč, M., 1991. Miocene strike-slip movement, faulting and block rotation in Breovské Karpaty Mts. Miner. Slov. Bratislava, 23: 189–200.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth Plan. Sci. Lett., 40: 25–32.

Meissner, R. and Stegena, L., 1988. Lithosphere and evolution of the Pannonian Basin. In: L.H. Royden and F. Horváth (Editors), The Pannonnian Basin; a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 147–152.

Morley, C.K., 1994. Discussion of origins of hinterland basins to the Rif-Betic Cordillera and the Carpathians. Tectonophysics, 226: 359-376.

Nagymarosy, A., 1981. Subsidence profiles of the deep Neogene basins in Hungary. Earth Evolut. Sci., 3-4: 218-222.

Nemčok, M., 1993. Transition from convergence to escape: field evidence from the West Carpathians. Tectonophysics, 217: 117-142.

Nemčok, M., Marko, F., Kováč, M. and Fodor, L., 1989. Neogene tectonics and paleostress field changes in the Czechoslovakian part of the Vienna Basin. Jahrb. Geol. Bundesanst., Wien, 132 (2): 443-458.

Oszczypko, N. and Slaczka, A., 1989. The evolution of the Miocene basins in the Polish Outer Carpathians and their foreland. Geol. Carpath., 40: 23-36.

Pěničková, M. and Dvořáková, V., 1985. In: Gaža et al., Final Report of the Hydrocarbon Prospection in the Danube Basin during 1973-1983. Geophys. Inst. Brno (in Czech)

Peper, T. and Cloetingh, S., 1992. Lithosphere dynamics and tectono-stratigraphic evolution of the Mesozoic Iberian rifted margin (southeastern Spain). Tectonophysics, 203: 345-361.

Pitman, W.C. and Andrews, J.A., 1985. Subsidence and thermal history of small pull-apart basins. Soc. Econ. Paleontol. Mineral. Spec. Publ., 37: 45-49.

Ratschbacher, L., Merle, O., Davy, Ph. and Cobbold, P., 1991. Lateral extrusion in the Eastern Alps, Part 1. Boundary conditions and experiments scaled for gravity. Tectonics, 225: 471-483.

Roth, Z., 1980. West Carpathians—Tertiary Structure of Central Europe. Library of the Central Geol. Inst. Prague, 55, 128 pp. (in Czech).

Royden, L.H., 1985. The Vienna basin: a thin-skinned pull apart basin. In: K. Biddle and K. Christie-Blick (Editors), Strike-Slip Deformation, Basin Formation and Sedimentation. SEPM Spec. Publ., 37: 319-339

Royden, L.H. and Dövényi, P., 1988. Variations in extensional styles at depth across the Pannonian basin system. In: L.H. Royden and F. Horváth (Editors), The Pannonian Basin, a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 235-255.

Royden, L.H. and Keen, C.E., 1980. Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves. Earth Planet. Sci. Lett., 51: 343-361.

Royden, L., Horváth, F., Nagymarosy, A. and Stegena, L., 1983. Evolution of the Pannonian basin system, 2. Subsidence and thermal history. Tectonics, 2: 91-137.

Rumpler, J. and Horváth, F., 1988. Some representative seismic reflection lines from the Pannonian basins and their structural interpretation. In: L.H. Royden and F. Horváth (Editors), The Pannonian Basin, a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 153-169.

Sauer, R., Seifert, P. and Wessely, G., 1992. Guidebook to excursions in the Vienna Basin and the adjacent Alpine-Carpathian Thrustbelt in Austria. Mitt. Öster. Geol. Ges. Wien, 85, 264 pp.

Sclater, J.G., Royden, L. Horváth, F., Burchfield, B.C., Semken, S. and Stegena, L., 1980. The formation of the Intra-Carpathian basins as determined from subsidence data. Earth Planet. Sci. Lett., 51: 139-162.

Seifert, P., 1992. Palinspastic reconstruction of the Easternmost Alps between Upper Eocene and Miocene. Geol. Carpath., 43: 327-333.

Špička, V., 1969. Analysis of thickness, distribution and evolution of the Neogene sediments in the area of the Vienna Basin. Zbor. Geol. Geol. Carpath., 11: 128-154 (in Czech).

Stegena, L., Géczy, B. and Horváth, F., 1975. Late Cenozoic evolution of the Pannonian basin. Tectonophysics, 26: 71-90.

Steininger, F.F., Rögl, F., Hochuli, P. and Müller, C., 1988. Lignite deposition and marine cycles, the Austrian Tertiary lignite deposits; a case history. Sitzungsber. Österr. Acad. Wiss. Math. Naturwiss., 197: 309-332.

Tari, G., Horváth, F. and Rumpler, J., 1992. Styles of extension in the Pannonian basin. Tectonophysics, 208: 203-219.

Tomek, Č., 1993. Crustal structure beneath the Central and Inner West Carpathians. Tectonophysics, 226: 401-433.

Tomek, Č. and Hall, J., 1993. Subducted continental margin imaged in the Carpathians of Czechoslovakia. Geology, 21: 535-538.

Tomek, Č. and Thon, A., 1988. Interpretation of seismic reflection profiles from the Vienna basin, the Danube basin and the Transcarpathian Depression in Czechoslovakia. In: L. H. Royden and F. Horvath (Editors), The Pannonian Basin. Am. Assoc. Pet. Geol. Mem., 45: 171-182.

Túnyi, I. and Kováč, M., 1991. Palaeomagnetic investigation of the Neogene sediments from the Little Carpathians. Contrib. Geophys. Inst. Slov. Acad. Sci., Bratislava, 21: 125-146.

Van Balen, R., Lenkey, L., Horvath, F. and Cloetingh, S., 1995. Two-dimensional modelling of stratigraphy and fluid flow in the Pannonian Basin. Am. Assoc. Pet. Geol. Bull., in press.

Van der Beek, P.A., Cloetingh, S.A.P.L. and Andriessen, P.A.M., 1994. Extensional basin formation mechanisms and vertical motions at rift flanks: constraints from tectonic modelling and fission track analysis. Earth Planet. Sci. Lett., 121: 417-433.

Vass, D., Kováč, M., Konečný, V. and Lexa, J., 1988. Molasse basins and volcanic activity in West Carpathian Neogene—its evolution and geodynamic character. Geol. Carpath., 39: 539-562.

Vass, D., Pereszlényi, M., Kováč, M. and Král, M., 1990. Out-line of Danube basin geology. Földtani Közlöny, Bull. Hung. Geol. Soc., 120: 193-214.

Vass, D., Hók, J., Kováč, P. and Elečko, M., 1993. The paleogene and Neogene tectonic events of the Southern Slovakia depression in the light of the stress-field analyses. Miner. Slov. Bratislava, 25: 79-92 (in Slovak).

Wernicke, G., 1985. Uniform sense simple shear of the continental lithosphere. Can. J. Earth Sci., 22: 108-125.

Wessely, G., 1988. Structure and development of the Vienna basin in Austria. In: L.H. Royden and F. Horváth (Editors), The Pannonian Basin, a Study in Basin Evolution. Am. Assoc. Pet. Geol. Mem., 45: 333-346.

Wessely, G., 1992. The Calcareous Alps below the Vienna Basin in Austria and their structural and facial development in the Alpine-Carpathian border zone. Geol. Carpath., 43: 347-354.