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Miocene tectonics at the Alpine-Carpathian junction and the evolution of the Vienna basin

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ABSTRACT

Early to Middle Miocene sediments of the Vienna Basin unconformably overly the Alpine-Carpathian nappes which were thrust over the European continental margin prior to the Middle Miocene. Structural analysis indicates three major tectonic stages in the Miocene evolution of the Alpine-Carpathian boundary area which correlate to distinct stages in the evolution of the Vienna Basin. These stages are:

(1) NW-directed thrusting and convergent wrench faulting during final foreland imbrication which lasted up to the Karpatian stage (c. 17 Ma). Deformation was characterized by the formation of ENE- to NE-striking sinistral wrench faults with prominent convergent strike-slip duplexes and flower structues. These faults root in the floor thrust of Alpine-Carpathian nappes and bound shallow, slowly subsiding Eggenburgian to Karpatian piggy-back basins.

(2) During late Early Miocene to Middle Miocene eastward lateral extrusion, NNE-trending sinistral fault zones transsected the older convergent faults. Sinistral faults extended from the central Eastern Alps into the outer Western Carpathians and formed the boundary of the extruding West Carpathian/West Pannonian wedge. In the Vienna Basin area, fault patterns depict NNE-oriented extensional duplexes. Duplexes are delimited by arrays of NE-striking sinistral faults and by NNE-striking normal faults which are arranged in left-stepping en-echelon patterns. Duplexing associated with substancial horizontal extension and normal faulting on NNE-striking faults was the main mechanism accounting for the rapid subsidence in the Middle Miocene Vienna pull-apart basin. Growth strata show that normal faulting occured from the Karpatian to the Pannonian (from 17-8 Ma). During 9 Ma, rift-type basement subsidence reached up to 5.8 km. Data as well as basin modelling results indicate that deformation during that time was restricted to the uppermost 10-12 km of the crust.

(3) During a Late Miocene stage of E-W directed shortening, Early and Middle Miocene sinistral faults were reactivated as dextral faults. This tectonic event terminated pull-apart subsidence as indicated by the ages of the youngest sediments in the Vienna Basin which belong to the Pannonian lithostratigraphic units G/H (c. 9-8 Ma). Miocene marine deposits cropping out at topographic heights between 300-400 m at the Alpine-Carpathian junction indicate that more than 300 m of regional surface uplift occured since the Pannonian.

Key words: Vienna Basin, Miocene kinematics, piggy-back basin, pull-apart basin

Introduction

The Miocene Vienna basin between the Eastern Alps, the Western Carpathians and the Pannonian basin system (Fig. 1), is one of the best documented large-scale pull-apart basins (Royden, 1985; Wessely, 1988). Due to extensive hydrocarbon exploration, geometry, stratigraphy and the tectonic architecture of the basin are well constrained. Subsurface data include subcrop maps, depth to basement maps, well sections, and seismic sections of OMV (e.g., Sauer et al., 1992; Brix and Schulz, 1993; Kröll and Wessely, 1993; Wessely et al., 1993). The interpretation of the basin as a pull-apart structure derived from the work by Royden (1985) who based her interpretation on the rhombohedral shape of the basin, on the left-stepping pattern of en-echelon faults in the basin, and on its position along a system of sinistral transfer faults between the Eastern Alps and the Western Carpathians (Fig. 2). These faults were interpreted as tear faults which linked active Early to Middle Miocene thrusts in the Carpathians with the Eastern Alps where thrusting had been already completed at that time (Fig. 1; Royden, 1985). However, new structural data from the Vienna basin and from the adjacent Eastern Alps (Decker et al., 1994; Decker and Lankreijer, in prep.; Fodor, 1995; Lankreijer et al., 1995; Linzer et al., in press; Peresson and Decker, in press) show a much more complex tectonic evolution. Accordingly, the basin evolved through three main tectonic stages which correlate to an early piggy-back basin phase, the proper pull-apart evolution, and to a phase of regional uplift and basin inversion.

The following discussion uses the stratigraphic correlation for the Central Paratethys by Rögl (this vol.; see also Steininger et al., 1990; Berggreen et al., 1995) for dating tectonic events, basin subsidence and uplift. Accordingly, the boundaries of the Central Paratethys stages are dated as 27.5 Ma (base Egerian), 18.3 (base Ottnangian), 17.2 Ma (base Karpatian), 16.4 Ma (base Badenian), 13.0 (+/- 0.2) Ma (base Sarmatian), 11.5 (base Pannonian), and 7.1 (base Pontian).

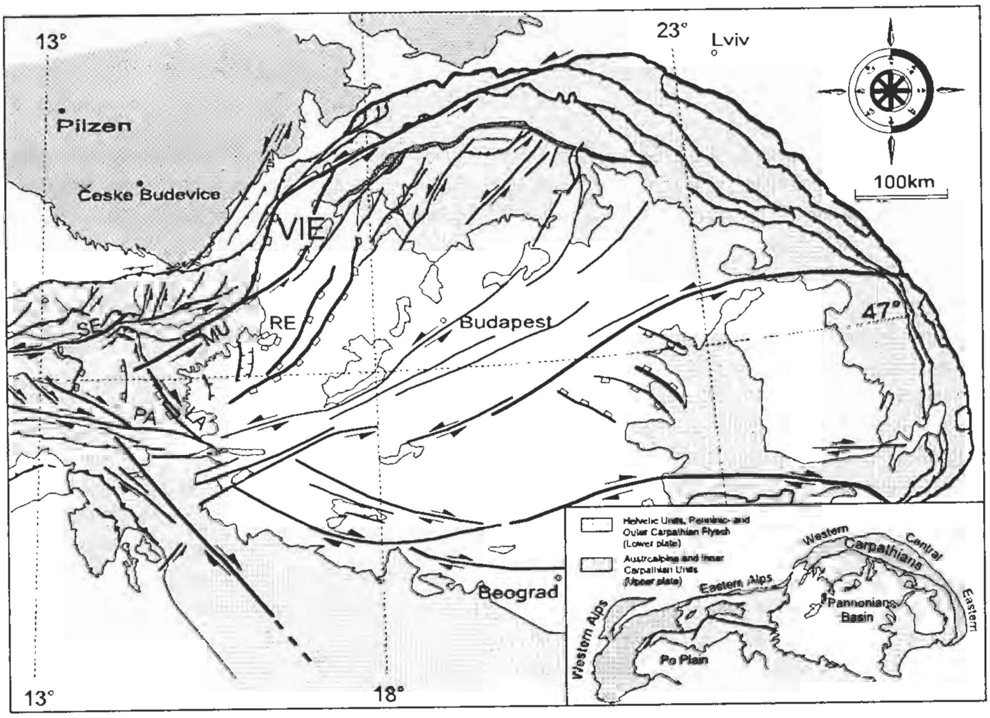

Fig. 1. Neogene tectonic map of the eastern Alpine-Carpathian-Pannonian area. Highlighted faults and shear senses illustrate the kinematics during the eastward lateral extrusion of fault-bounded wedges from the Eastern Alps towards the Carpathian-Pannonian area. The Vienna Basin is situated at the left-step of the transform system which is traced from the Salzach-Ennstal (SE) and Mur-Mürz (MU) fault system in the Eastern Alps into the Western Carpathians. Also labeled are the Periadriatic fault (PA), the Lavanttal fault array (LA), and the Rechnitz core (RE).

Tectonic setting

The Vienna basin overlies the thin-skinned nappes of the Alpine-Carpathian thrustbelt which were thrust over the European passive margin between the Middle Eocene and the Early Miocene (c. 47 and 17 Ma). From base to top, crustal sections through the Vienna Basin (Wessely, 1993; Fig. 3) show: (1.) The Neogene basin fill. Early Miocene (Eggenburgian, c. 22 Ma) to Late Miocene (Pannonian, c. 8 Ma) clastic sediments and subordinate shallow-water limestones (Leithakalk Fm.) reach up to 5.8 km thickness. (2.) The Alpine-Carpathian thrust sheets which reach a maximum thickness of about 8 km below the basin. Neogene sediments unconformably overly nappes of the Silesian and Penninc flysch units, Mesozoic and Palaeozoic cover nappes of the Austroalpine nappe complex, and Austroalpine crystalline basement nappes (Wessely et al., 1993). The floor thrust of these thrust sheets crops out 10 to 20 km NW of the basin margin and dips to 8 to 12 km depth in the SE part of the basin (see sections by Tomek and Hall, 1993; Wessely, 1993). (3.) The Bohemian crystalline basement with Paleozoic sediments and a Jurassic to Tertiary sedimentary cover. The latter sequences were depostited on the thinned passive European continental margin which rifted during the Jurassic.

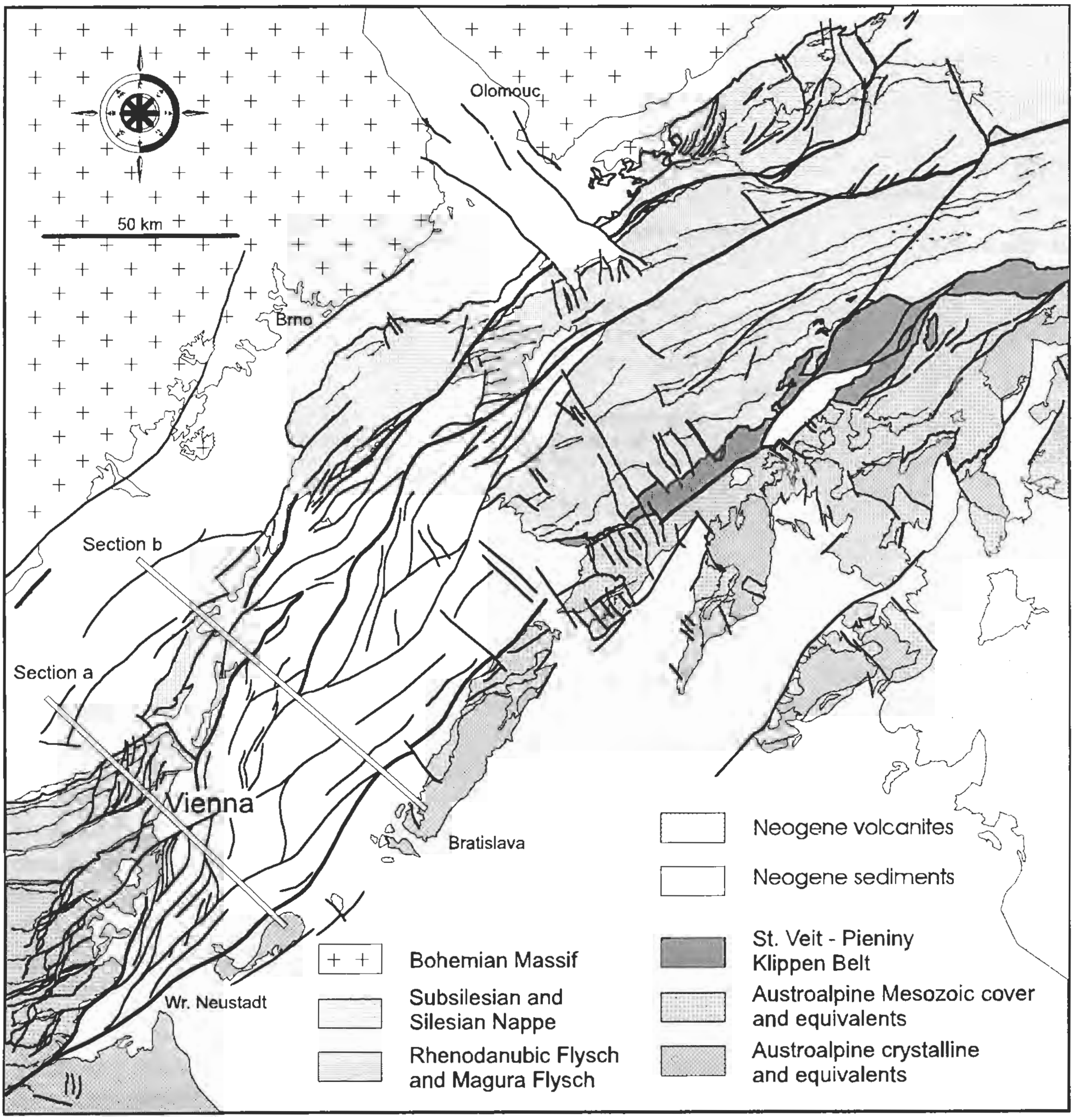

Fig. 2. Tectonic map of the Vienna Basin and adjacent areas. Note the rhombohedral fault patterns defined by NE- and NNE-trending faults. Synthesized from geological maps by Fuchs and Grill (1984), the Geological Maps 1 : 200.000 of former Czechoslovakia, and the Vienna Basin subcrop map by Kröll and Wessely (1993).

Sedimentation in the Vienna basin between the Eggenburgian and the early Karpatian (c. 22 to 17 Ma) overlapped with the final stages of thrusting (Fig. 4). The E-W-trending shallow piggy-back basin only covered the northern part of the subsequently formed pull-apart basin (Seifert, in: Sauer et al., 1992). Early Miocene kinematics at the Alpine-Carpathian boundary were characterized by the combination of thrusting and wrenching which was caused by the shape of the European foreland and by the corner effect of the Bohemian promotory. The pinning of the thrust front south and west of the promotory and the foreland recess east of it caused superposition of thrusting and wrenching during thrusting into the recess. The piggy-back basin compares to Early Miocene basins which developed along wrench faults in western Slovakia (Kovac et al., 1989; Marko et al., 1991).

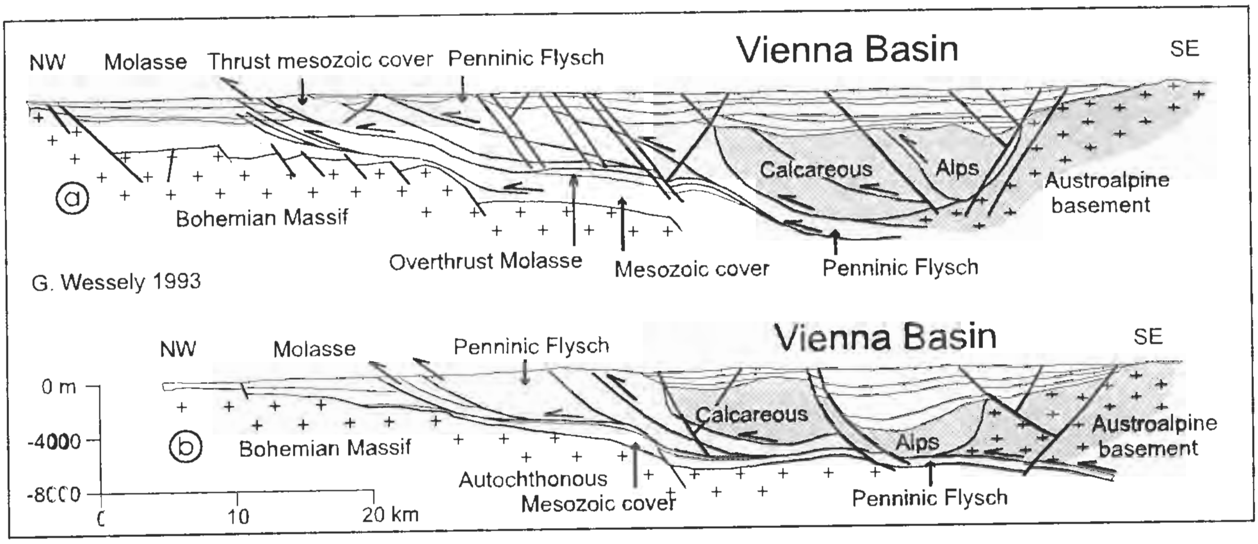

Fig. 3. Schematic cross-sections through the central (a) and southern (b) Vienna Basin after Wessely (1993). See Fig. 2 for location of the sections.

The termination of thrusting east and west of the Bohemian promotory at about 17 Ma (Karpatian, late Early Miocene) is dated by the biostratigraphic ages of the youngest overthrust molasse sediments (Brix et al., 1977; Wagner et al., 1986; Poprawa and Nemcoc, 1988-1989). During the Early Miocene, the style of post-collisional shortening in the Eastern Alps changed from thrusting to eastward lateral extrusion (Royden et al., 1983; Royden, 1988; Ratschbacher et al., 1991a, b; see also Peresson and Decker, this vol.). The extruding wedges of the central Eastern Alps moved eastwards between (E)NE-striking sinistral faults (Salzach-Ennstal fault, Mur-Mürz-fault) and (E)SE-trending dextral faults (Fig. 1). During the Karpatian stage (17.3 - 16.4 Ma), the Vienna basin evolved into a pull-apart basin. The sinistral strike-slip system hosting the basin extended from the central Eastern Alps into the flysch units of the outer Western Carpathians (Fig. 1, 2). NE of the basin, the Subsilesian and the Silesian nappes were cut by the Schrattenburg-Bulhary fault. This fault terminated in a prominent extensional imbricate fan NE of the basin (Fig. 2). A second major fault NE of the basin transsected the Magura nappe and formed the boundary between Silesian nappe and Magura flysch further NE (Fig. 1; Decker and Peresson, in press).

Cross-sections through the central and southern Vienna Basin (Wessely, 1993; Fig. 3) show a general assymetry of the basin. The neogene sediments form westward thickening wedges which are bounded to the west by synsedimentary faults. The two most important of these east-dipping normal faults, the Steinberg and the Leopoldsdorf faut system with 5 and 3 km normal offset, respectively, are situated close to the NW basin margin. Both faults probably root in the (S)E-dipping floor thrust of the Alpine-Carpathian nappes or in a detachment horizont within the autochthonous Jurassic sediments of the Bohemian crystalline basement (see Tarti, this vol.). This may indicate that a component of top-to-(S)E detachment faulting during lateral extrusion combined with sinistral faulting and pull-apart formation.

Lateral extrusion and eastward motion of wedges along the NE-striking sinistral faults ended during the Late Miocene (see Peresson and Decker, this vol.). This kinematic change was forced by a switch of the far-field stresses to E-W-directed compression which has been documented in the Eastern Alps, in the western Carpathians and in the Pannonian region (Peresson and Decker, in press). In the Vienna basin, this event led to the termination of basin subsidence during the Pannonian.

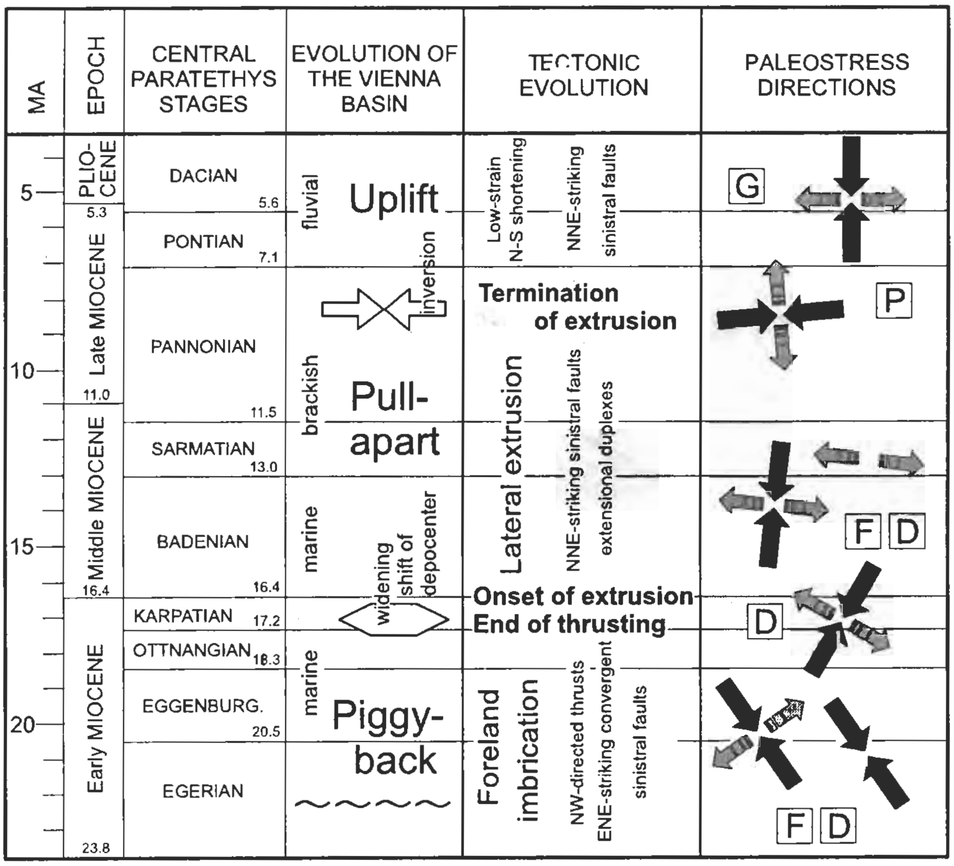

Fig. 4. Timing of the evolution of the Vienna Basin and correlated tectonic events at the Alpine-Carpathian junction. Columns (from left to right) refer to the sedimentary basin evolution, tectonic events and fault kinematics, and to paleostress directions according to Gutdeutsch and Aritsch, 1976 (A), Fodor, 1995 (F), Peresson and Decker, in press (P) and Decker and Lankreijer, in prep. (D).

Miocene kinematics in the southern Vienna Basin area

In the following paragraph, fault-slip data which constrain the geometries of fault patterns and fault kinematics during Miocene basin subsidence are reviewed. Data from outcrops in the Calcareous Alps at the SW basin margin are compared to subcrop fault patterns in the Vienna Basin itself. Three major tectonic phases during the Neogene are indicated (Fig. 4): (1) NW-directed thrusting and convergent wrench faulting associated with the formation of piggy-back basins; (2) formation of divergent strike-slip duplexes and oblate horizontal extension during pull-apart basin formation; and (3) E-W directed shortening associated with low-strain. The relative chronology of these events is deduced from both cross-cutting map-scale faults and from overprinted microtectonic structures.

(1.) Thrusting, convergent wrenching and piggy-back basin fromation

Up to the Early Karpatian (c. 17 Ma), sedimentation in the Vienna Basin was restricted to a shallow piggy-back basin which only covered the northern part of the Middle Miocene pull-apart basin. This piggy-back basin was characterized by an E-W trending basin axis stiking oblique to the later pull-apart basin and by very low subsidence (Sauer et al., 1992; Lankreijer et al., 1995). It can be compared to Early Miocene basins in the Wetsern Carpathians which show evidence for synsedimentary thrusting and wrench faulting, WSW-ENE oriented basin axis paralleling the boundary faults, and low subsidence (Kovac et al., 1989; Marko et al., 1991).

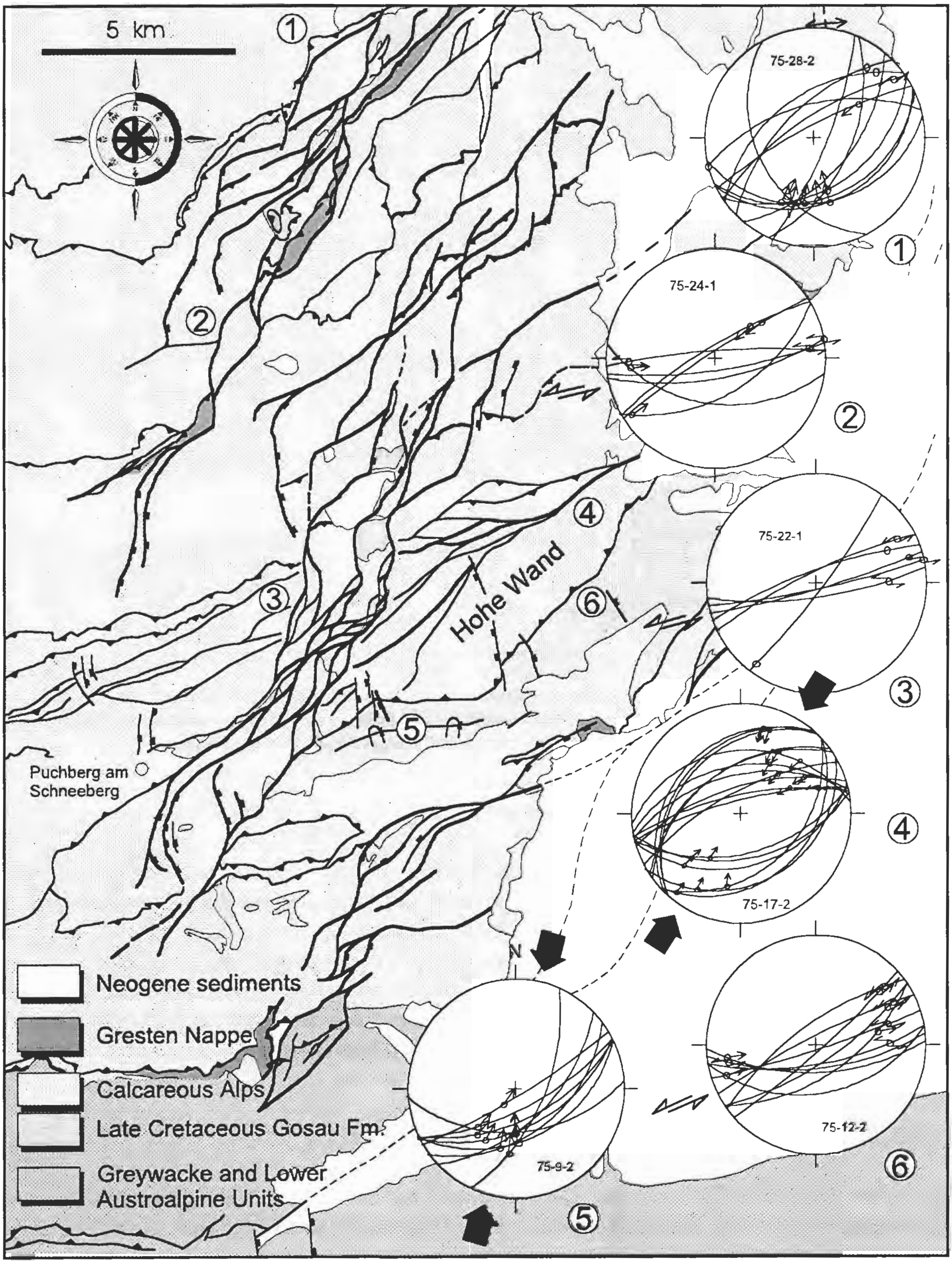

Fig. 5. Tectonic map of the southwestern margin of the Vienna Basin based on the geological map by Summesberger (1991). Examples of fault-slip data from ENE-trending strike-slip faults and convergent duplexes are shown. Numbers refer to the location of the field stations indicated in the map.

The formation of Early Miocene basins on the Alpine-Carpathian thrust sheets during protracted thrusting was controlled by ENE-trending sinistral wrench faults which are correlative to faults mapped in the easternmost Calcareous Alps (Fig. 5). The geometries of such ENE- to NE-striking sinistral faults show prominent convergent strike-slip duplexes of about 1 to 5 km length. Several major faults display convex-up geometries and oblique-reverse slip vectors typical for convergent flower structures (plot 4, Fig. 5). At the Hohe Wand range, Triassic sequences were thrust over folded and overturned Late Cretaceous sediments of the Gosau group (plots 5 and 6, Fig. 5).Within the convergent structures, sequences from the deep stratigraphic levels of the Calcareous Alps (Permian evaporites, Early Triassic marls) and from the Helvetic Gresten nappe which underlies the Calcareous Alps were uplifted. The presence of Helvetic sequences and the absence of deeper overthrust units like Flysch or Molasse sediments indicate that the convergent faults root in the floor thrust of the Calcareous Alps. The wrench faults partly followed prae-existing NW-striking thrust planes within the Calcareous Alps. Sinistral offsets cannot be estimated as the faults parallel regional strike. Sinistral convergent wrench structures of the Calcareous Alps correlate to the positive flower structure of the Brezova Unit in the Western Carpathians which formed during sinistral motion of the Dobrá Voda fault zone (Marko et al., 1991). Timing of fault motion there is constrained by faulted and thrust Eggenburgian to Karpatian rocks.

(2) Divergent sinistral faulting, oblate(?) horizontal extension and pull-apart basin formation

Thrusting and convergent wrenching terminated during the Karpatian stage (c. 17 Ma) when regional deformation changed to eastward lateral extrusion. Paleogeographic reconstructions show that the Vienna Basin acquired its present rhomb-shape during the same time (Sauer et al., 1992). The change from the piggy-back basin to the evolution of the pull-apart basin therefore occured in less than 1 Ma. Basin evolution from the Karpatian to the Pannonian (c. 17 to 8 Ma) was characterized by strongly accelerated rift-type basement subsidence which reached up to 5.8 km in about 9 Ma. Thickness maps of the Neogene basin fill (Kröll and Wessely, 1993) show two separate depocenters in the northern and southern part of the 120 km long and 60 km wide basin. Subsidence was governed by sigmoidal N- to NNE-trending faults with major components of normal offset (Kröll and Wessely, 1993). For many normal faults growth strata show that faulting occured synsedimentary during the late Early and Middle Miocene. The normal faults developed in NE-directed left-stepping en-echelon patterns which were probably linked by NE-trending sinistral strike-slip faults. These scale-invariant patterns closely resemble geometries of extensional strike-slip duplexes with lengths of several hundret meters up to the outline of the entire basin (Fig. 2).

Late Early Miocene and Middle Miocene NNE-trending extensional duplexes in the Vienna Basin correlate to duplex-style fault patterns in the Calcareous Alps which there transsected the Early Miocene convergent wrench faults (Fig. 6). NNE-trending faults zones crosscutting older ENE-striking wrench faults comprise arrays of divergent strike-slip duplexes which are few hundret meteres to about 1 km long. These divergent fault systems are characterized by up to 1.5 km broad zones of intense faulting and fracturing. Three such deformation zones, each accounting for 3.5 to 4.5 km sinistral offset, occur at a regular spacing of about 3 km in the easternmost Calcareous Alps (Fig. 6). Several duplex arrays comprise down-thrown Late Cretaceous Gosau formations which are sandwiched between Triassic units. Fault-bounded Early Pannonian konglomerates which are confined to one of the fault zones argue for Miocene deformation ages (Fig. 6). To the S, the NNE-striking deformation zones terminate in extensional imbricate fans with E-dipping normal- and oblique-normal faults. Rhomb-shaped duplexes within the deformation zones are bound by parallel sets of NNE- and NE-striking faults, the latter following prae-existing Early Miocene wrench faults. The reactivation of these wrench faults which root in the floor thrust of the Calcareous Alps indicates that extensional duplexing very likely was restricted to the uppermost tectonic uints of the Alpine-Carpathian thrust wedge.

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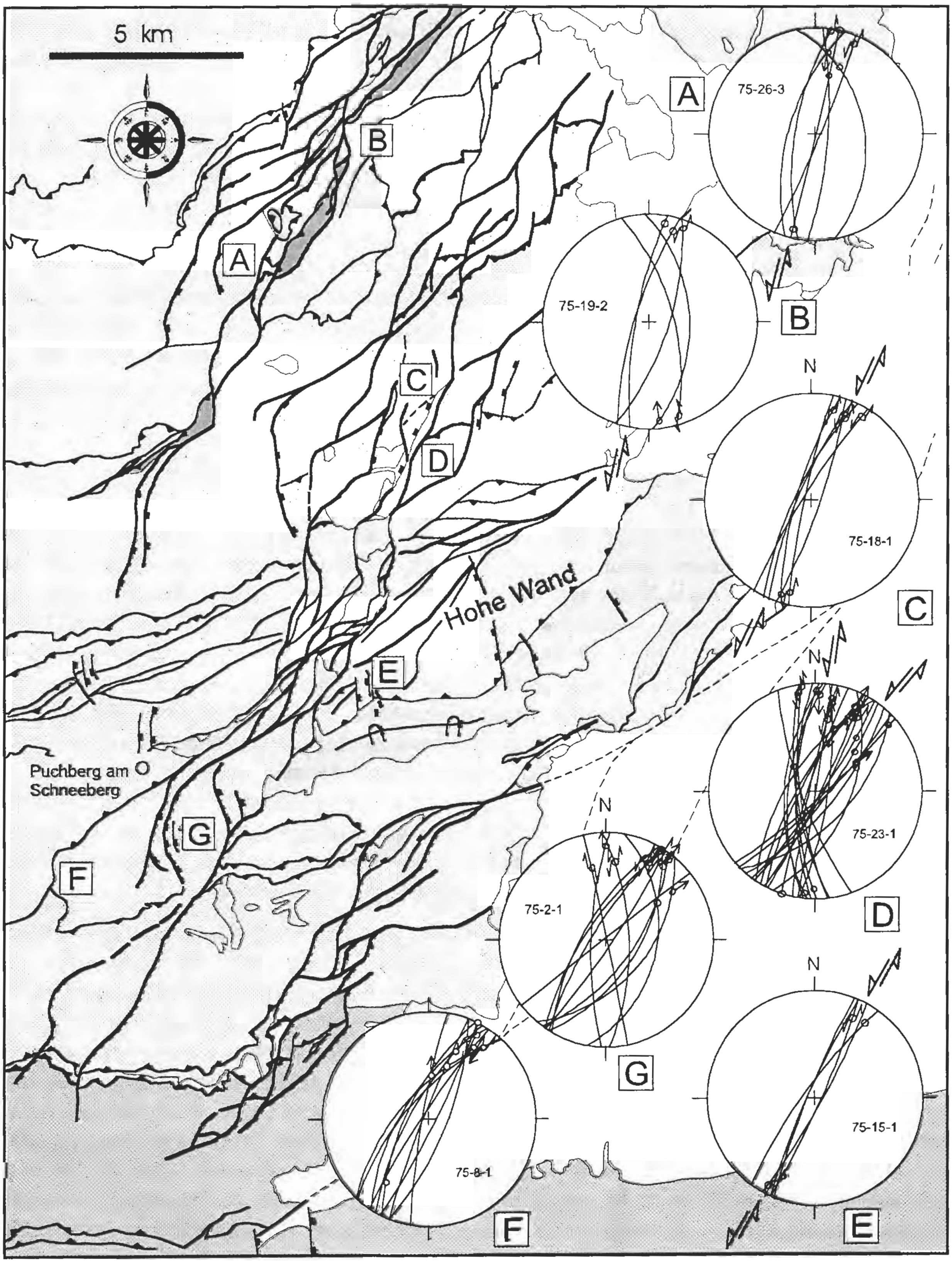

Fig. 6. Tectonic map of the southwestern margin of the Vienna Basin based on the geological map by Summesberger (1991). Microtectonic fault-slip data from NNE-trending strike-slip faults and divergent duplexes are shown. Note the P-shear/Riedel shear fault geometries depicted in plot D. Letters refer to the location of the field stations indicated in the map.

Microfault assamblages are dominated by P-shear/main fault/Riedel-shear geometries. Extensional duplexing was associated with and followed by prominent extensional faulting. Normal-slip reactivation also affected formerly convergent wrench faults. Dip directions of both normal faults and sliplines are highly variable and, together with the lack of consistent cross-cutting relationships, do not allow to constrain distinct phases of differently oriented extensional faulting (Fig. 7). The only exceptions are NNE-directed extensional structures which consistently overprint variably oriented older extensional faults (Fig. 7, plots from station 5) and which correlate to prominent (E)SE-striking map-scale normal faults in the Western Carpathians E of the basin (Fig. 2). These faults also clearly cut the (N)NE-striking boundary faults of the basin. It is concluded that extension during divergent strike-slip duplexing apporximated oblate strain geometry and that the formation of the NE-striking duplexes was followed by a distinct period of NNE-SSW-oriented extension.

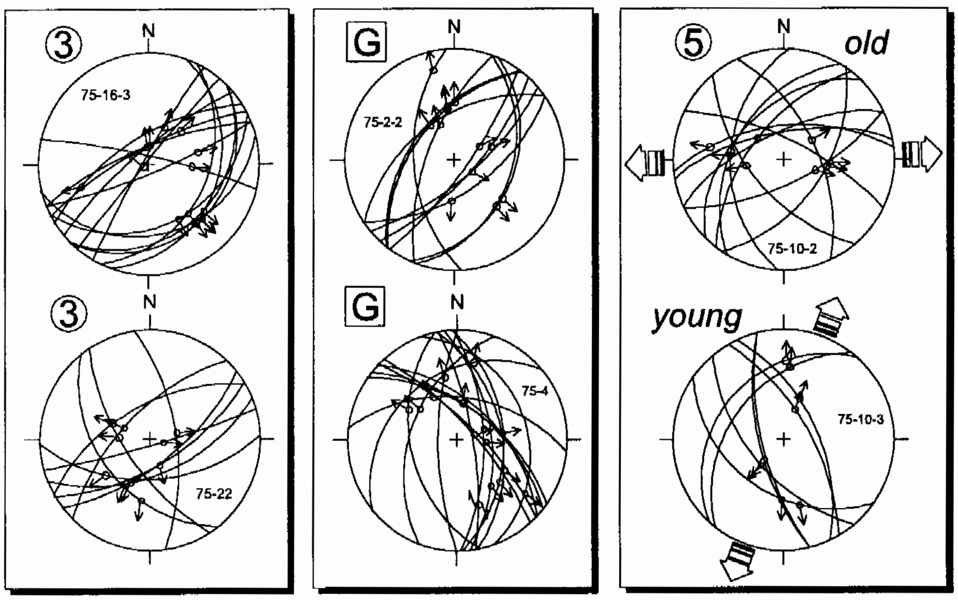

Fig. 7. Examples of sets of extensional faults with highly variable orientations approximating oblate finite strain. The only consistently observed overprinting relationships among normal faults indicate a younger phase of NNE-directed extension (station 5, plots 75-10-2 and 75-10-3). Letterings refer to the location of the field stations indicated in Fig. 5 and 6.

(3) E-W directed shortening and the termination of pull-apart subsidence

E-W shortening as one of the youngest tectonic events in the Vienna Basin area is indicated by overprinting microtectonic structures which proof the reactivation of Early and Middle Miocene faults (see Peresson and Decker, this vol.). Strain of E-W shortening and dextral offset of the NE-striking, formerly sinistral faults cannot be quantified but it seems to be low compared to the strain of the earlier tectonic phases. Folded Early Pannonian strata which crop out at the southern margin of the Vienna Basin and the correlation to simmilar structures in the Pannonian Basin and in the Outer Carpathians allow to date the E-W compressive event as late Pannonian (about 9 to 5.6 Ma; Peresson and Decker, in press). This deformational age conforms with the age of the younges depostits in the Vienna Basin which belong to the Pannonian lithostratigraphic units G and H (mammal biostratigraphic zones MN 10 and MN 11, c. 9 to 8 Ma; Rögl et al., 1993; Rögl, this vol.). Significant volumes of sediments younger than Pannonian (i.e., Pontian and Pliocene) are not known in the Vienna Basin (Rabeder and Rögl, pers. comm.). The only exceptions are local fluviatile gravels of possible Pontian age which unconformably overly Pannonian sediments and which postdate the pull-apart subsidence of the basin.

Neogene marine deposits cropping out at maximum topographic heights between 300-400 m at the margin and in the northern part of the Vienna basin indicate substancial post-Pannonian surface uplift (Fig. 8). Uplifted marine Sarmatian sediments and brackish Pannonian sediments (lithostratigraphic unit F; Rögl et al., 1993) give only loose time contraints for this event which must have occured in the last 8 Ma. Taking into account that the Early Pannonian (Seravallian) sea level in the the Mediterranean region was about 50 m above the recent level (Vail et al., 1977), surface uplift must have exceeded 300 m. Data from adjacent areas indicate that post-Pannonian surface uplift of several hundret meters also occured in the SE Bohemian Massif (Horn Basin, (1) in Fig. 8), in the Molasse foredeep of the Eastern Alps (Genser and Neubauer, 1996), in the Western Carpathian foredeep (Zoetemeijer et al., this vol.), and in the Styrian Basin (Sachsenhofer, this vol.). Late Miocene/Pliocene surface uplift therefore was of regional importance in the entire Alpine-Carpathian-Pannonian boundary area.

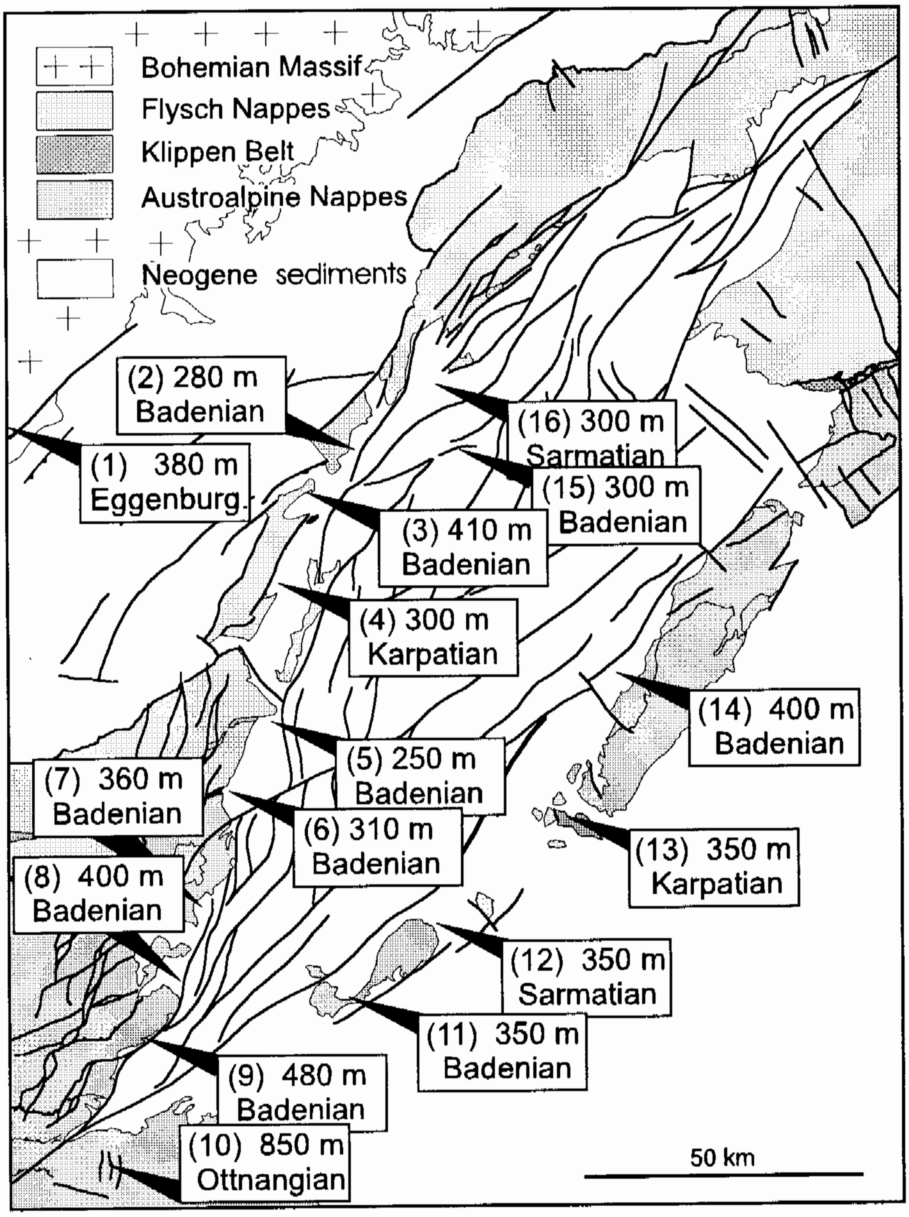

Fig. 8. Maximum topographic altitude of Neogene marine deposits at the Vienna Basin margin indicating 300-400 m post-Sarmatian regional uplift. Uplifted units: (1) Horn Basin, Lithothamnion limestones; (2, 3) Waschberg zone, Badenian shore facies; (4) Korneuburg Basin; (5, 6) Vienna, marine basinal marls („Tegel"); (7, 8, 9) marine fan-deltas of the Baden- and Lindabrunn Fm.; (10) Wechsel, Kirchberg Fm.; (11 to 14) Leithakalk Fm.; (15, 16) Badenian and Sarmatian marine sediments in the footwall of the Steinberg fault.

Constraints on the crustal-scale deformation in the Vienna Basin

Crustal sections through the Vienna Basin show three superposed tectonostratigrahic untits. From top to base, these are (1.) up to 5.8 km thick Neogene sediments of the Vienna basin; (2.) the Alpine-Carpathian thrust sheets whith a floor thrust which dips from about 6 km below the NW part of the basin to 8 - 12 km depth below the SE part (Wessely, 1993; Fig. 3); and (3.) the Bohemian crystalline basement with its autochthonous sedimentary cover.

Normal faults in the Vienna Basin mapped by seismic data show that extension only affected the allochtonous units and that normal faults did not or not significantly offset the European crust (Wessely, 1983; 1993). According to this interpretation, the normal faults root in the floor thrust of the Alpine-Carpathian nappes or in a detachment within the autochthonous cover of the Bohemian crystalline. The largest normal faults in the Vienna Basin, the Steinberg- and Leopoldsdorf fault whitch account for 5 and 3 km normal offset, respectively, display roll-over and growth-strata geometries which indicate listric fault geometries and flattening of the faults in depth (Krainer, pers. com.; Wessely, 1983). Such evidence for a thin-skinned nature of extension which only affected the uppermost crust in the Vienna Basin area is corroborated by crustal thicknesses at the Alpine-Carpathian-Pannonian junction which shows crustal thicknesses of more than 30 km beneath the Vienna basin (Posgay et al., 1989). The transition to the thinned crust of the Pannonian region is situated east of the Vienna Basin. Additional arguments for thin-skinned extension come from basin modelling results (Decker and Lankreijer, in prep.). (W)NW-(E)SE-oriented interpreted sections through the Vienna Basin by Wessely (1993) show that up to 5.8 km basement subsidence in 9 Ma were associated with only about 20% to 30% extension parallel to the sections. It can be shown that this subsidence history is not in accordance with lithospheric stretching models which are based on the McKenzie model. Such subsidence, however, can readily be explained by strain-dependent thin-skinned extension in which stretching is confined to the uppermost crust. Finally, also the low heat flow values recorded in the basin (c. 40 to 60 mW/m^2; Dövényi and Horvath, 1988) argue against lithosphaeric stretching. Heat flow within the basin is even lower than heat flow estimated for the adjacent Alpine thrust belt and the Bohemian Massif. Finite difference modelling by Grasemann et al. (in prep.) shows that this thermal structure of the basin can be explained by a thin-skinned extensional model.

Acknowledgements

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