3-D mapping of segmented active faults in the southern Vienna Basin

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Abstract

In this paper we present novel data on the location and kinematics of seismically active fault segments of the Vienna Basin Transfer Fault System in the southern Vienna Basin. Spatial mapping of active faults and kinematic analyses are based on commercial 3-D reflection seismic data, geomorphological features such as tilted Quaternary river terraces and fault scarps, the geometry of subsided Quaternary basins, and published geodetic data. Accordingly, active faulting in the southern Vienna Basin occurs partly by reactivation of the Miocene fault system related to the formation of the Vienna pull-apart basin between c. 17 and 8 Ma. Two domains of Quaternary and active faults can be distinguished with, (1) predominantly strike-slip and (2) mainly normal faulting. (1) A seismically active NE-striking sinistral strike-slip fault zone with large negative flower structures is mapped at the south-eastern margin of the basin. Subsidence within the reflection seismically imaged flower structure is documented by up to 1000 m of throw since Pannonian times and the accumulation of up to 150 m thick Quaternary gravels. At the surface the fault zone is characterized by en-echelon faults with some prominent scarps. (2) Major E-dipping normal faults branch off from the transfer strike-slip fault system. The normal faults extend into the central and western part of the basin as well as into the urban area of Vienna. Close to Vienna, the normal offset along such a normal fault is at minimum 300 m since Pannonian times. Surface expressions of active normal faulting are tilted Quaternary terraces of the Danube river and tilted ancient land surfaces in the hanging wall of the normal faults. The mapped active normal faults are kinematically linked by a common detachment horizon, which is in contact with the seismically active strike-slip zone along the south-eastern border of the basin. Northeast of the Vienna Basin the seismically active zone continues as a straight line indicating a rather linear transfer fault zone than a pull-apart step over geometry.

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1. Introduction

The southern Vienna Basin is a prominent site of moderate seismicity with medium sized earthquakes ($M_0 \sim 5.0–5.5$) returning at periods of several decades (ZAMG, 2001; e.g., Schwadorf 1927 with $M = 5.2$; Fig. 1). The distribution of earthquake epicentres, active fault kinematics resolved from focal solutions, and the few available dynamic data suggest that earthquakes occur on reactivated faults of the Vienna Basin Transfer Fault System, which are inherited from Miocene strike-slip faulting and pull-apart formation (Decker et al., 2005). Miocene deformation in the Vienna Basin was distributed over a dense network of kinematically linked faults covering the entire area of the basin and the adjacent basin margins. These faults are generally very well known due to extensive hydrocarbon exploration in the basin providing several thousand kilometres of 2-D seismic, c. 500 km$^2$ of 3-D seismic data, and several thousand drill holes (Sauer et al., 1992; Kröll and Wessely, 1993). Major faults typically are spaced at distances of only few kilometres showing splays and branches, and converge to depth (Fig 1). The past kinematics of the faults and their interaction has been analysed by several studies (Fodor, 1995; Decker, 1996; see Decker et al., 2005, for a review).
Geological evidences of active faulting in the Vienna basin is usually limited to sparse single outcrops (e.g., Kümmel, 1935; Fink et al., 1958; Küpper, 1971) or have been inferred from lineament analysis of remote sensing data (Häusler et al., 2002). Therefore, the knowledge of the location of active faults and their kinematics is very low in contrast to the accurate data on Miocene faults. This is mainly due to the limited accuracy of available earthquake hypocenter determinations with errors of several kilometres both in
horizontal and vertical directions. Earthquake location errors are typically larger than the spacing of mapped Miocene faults and do not allow to discriminate active and inactive faults. As a result, it is not known, where exactly the active faults are located, how they are segmented and how these segments interact kinematically. However, such data are among the most important input parameters for realistic seismic hazard estimates in a densely populated and highly vulnerable region such as the Vienna Basin, e.g., for estimating the maximum magnitude of a future earthquake (Schwarz and Coppersmith, 1984; Wells and Coppersmith, 1994). In general, geological data might contribute to determine seismogenic fault segmentation as major geometric bends at faults often coincide with segment boundaries (Cowie and Scholz, 1992; Stewart and Taylor, 1996). The need for updated tectonic datasets is stressed by the recent finding of a considerable seismic slip deficit along the Vienna Basin Transfer Fault System (Hinsch and Decker, 2003). It is shown that seismic deformation computed from the seismic moment release of historical earthquakes accounts only for 10–20% of the geologically determined slip rates of c. 2 mm/yr across the fault system (Grenerczy et al., 2000; Grenerczy, 2002a, 2002b; Decker et al., 2005). At present it is not clear whether this slip deficit indicates an underestimated seismic potential of the fault system, or it is related to distinct mechanical conditions along different fault segments.

Available seismic hazard estimates for eastern Austria are based on probabilistic analyses of historical earthquakes and refrain from the use of any fault-related data (Lenhardt, 1995, 1996; Grünthal et al., 1998). It is the major purpose of this paper to seed a fault-related database pinpointing locations of active faults, to show up possible fault segmentation, and to assess active kinematics in order to better constrain possible locations of future earthquakes, their probable depths and maximum expected magnitudes. Mapping of active faults in the southern Vienna Basin and the assessment of present fault kinematics is based on the interpretation of a 3-D reflection seismic survey covering one of the seismically most active parts of the Vienna Basin Transfer Fault (3-D seismic survey Moosbrunn, OMV AG, Austria). Seismic interpretation is combined with geomorphological data (high resolution Digital Elevation Models), and the distribution and thickness of Quaternary sediments to distinguish active faults from inactive Miocene ones. The results backup a regional map of active faults (i.e. Pleistocene to recent) and provide the basis for the discussion of a novel model of fault segmentation and active kinematics, which is in agreement with seismological, geotectonic and geological data.

2. Geological background

2.1. Tectonic setting, seismicity and recent kinematics

The Vienna Basin is a regional depression between the Eastern Alps and the Western Carpathians located along the Vienna Basin Transfer Fault (Vienna Basin Transfer Fault; Fig. 1 inset). This fault developed during Miocene eastward lateral extrusion of crustal blocks from the Eastern Alps to the Carpathian-Pannonian region (Ratschbacher et al., 1991; Linzer et al., 1997, 2002). The Vienna Basin represents a thin-skinned Miocene pull-apart basin with a left stepping geometry at the sinistral Vienna Basin Transfer Fault, which is considered to root on the basal detachment of the Alpine–Carpathian orogenic wedge at depths between 8 and 12 km (Royden et al., 1983; Royden, 1988). The basin is a classical pull-apart structure with a rhomboidal shape and two depocentres (Fig. 1). The structural map of the pre-Miocene basement (Kröll and Wessely, 1993) shows that the faults with the largest dip-slip offset are located at the western border of the basin resulting in a large-scale asymmetry of the basin (e.g., Leopoldsdorf and Steinberg Fault, Fig. 1). These, partly listric faults accumulate up to 5 km normal offset and branch off from the sinistral strike-slip faults at the border, though opening the pull-apart basin. The major branch point of the Leopoldsdorf Normal Fault in the southern Vienna basin is located within the 3-D seismic dataset investigated in this study (Fig. 1).

Observed seismicity (Fig. 1) as well as offset Quaternary sediments prove continued fault activity along the Vienna Basin Transfer Fault (Aric and Gutdeutsch, 1981; Gutdeutsch and Aric, 1988; Decker and Peresson, 1998; Hinsch and Decker, 2003; Decker et al., 2005). The seismicity pattern along the Vienna Basin Transfer Fault highlights a 400 km long and c. 30 km wide zone paralleling the Miocene fault system (Gutdeutsch and Aric, 1988). Recorded seismicity within the Vienna Basin area predominantly lines up at the southeastern border of the basin in prolongation with the seismically active zones in the Eastern Alps and the Western Carpathians (Gutdeutsch and Aric, 1988; Fig. 1). Recent stresses and focal mechanisms from earthquakes along the Vienna Basin Transfer Fault mostly indicate sinistral strike-slip faulting along north-east striking subvertical faults (Gangl, 1975; Marsch et al., 1990; Reinecker and Lenhardt, 1999; Reinecker, 2000). These data are consistent with GPS observations indicating approximately 2 mm/yr sinistral movement of the Vienna Basin Transfer Fault (Grenerczy et al., 2000; for a regional kinematical overview compare Fig. 1 of Decker et al. 2005). For the present kinematics it is not clear whether the fault system still represents a pull-apart system or rather a linear strike-slip fault at the southern border of the basin.
2.2. Sedimentary evolution and stratigraphy of the Vienna Basin

The structural interpretation of 3-D seismic data utilizes a very well constrained stratigraphic framework (Sauer et al., 1992; Seifert, 1996), which is correlated to the Paratethys chronostratigraphy (Rögl, 1996). The sedimentary evolution of the Vienna Basin started during the Early Miocene (Eggenburgian–Ottangian–Karpatian; c. 20–17 Ma) with the development of a partly non-marine piggyback basin on top of N-to NW-moving Alpine thrust units (Decker, 1996). Around the Early/Middle Miocene boundary (c. 17 Ma) kinematics changed to sinistral transtension (Fodor 1995; Decker, 1996), initiating pull-apart subsidence and marine transgression in the central part of the basin. Marine sedimentation in the southern part of the basin commenced during the Early Badenian. During the Badenian and Sarmatian, the rapidly subsiding marine basin was filled with up to 3000 m thick successions of marls and sandstones (central parts of the basin), as well as delta sands and carbonates (basin margins; Sauer et al., 1992; Weissenbäck, 1995; Seifert, 1996). Decreasing salinity during the Sarmatian and Pannonian leads to limnic-fluvial deposition (Seifert, 1996). Within the central part of the basin, unconformities and erosion are very minor. Maximum water depths probably never exceeded 250 m as subsidence was approximately matched by sedimentation. Miocene syntectonic sedimentation is expressed in a stack of depositional sequences with distinct seismic facies and partly growth-strata.

Seismic facies and stratigraphic geometries are depicted in the 3-D seismic survey and stratigraphic units are readily correlated across faults and linked to the chronostratigraphic framework by borehole control in order to assess both fault offsets and the timing of faulting.

3. Mapping of faults in 3-D seismic data

For mapping of subsurface faults we interpret the 3-D seismic survey Moosbrunn (OMV Austria, Figs. 1 and 2). Stratigraphic information is obtained by three wells within the survey (Fig. 2). The wells are tied to the seismic by velocity information provided by OMV (for the Neogene sediments 1 s TWT correspond to c. 1100 m depth, 2 s TWT to c. 2600 m and 2.5 s TWT to c. 3500 m).

The area of the 3-D seismic survey covers the zone of highest seismicity along the south-eastern margin of the Vienna Basin southeast of Vienna (Figs. 1 and 2). The surface topography of this area is characterized by a prominent elevated plateau within the otherwise very flat southern Vienna Basin (Rauchenwarth Plateau; Figs. 2 and 3a). A prominent linear morphological scarp delimits this plateau to the southeast. The scarp corresponds to the northeast-trending boundary between Late Miocene (Pontian) strata outcropping on the elevated plateau and up to 150 m thick Quaternary sediments of the Mitterndorf Basin below the scarp (Figs. 3b and 4).

3-D seismic data show that the scarp is underlain by an array of faults, which is illustrated using two sections perpendicular to the fault zone (Sections A and B), one section paralleling the scarp of the Rauchenwarth Plateau (Section C), and an attribute map covering the entire area of the survey including the scarp (Figs. 5–8). In the following description alphabetical labels and numbers are used to identify main fault blocks and main faults, respectively (inset in Figs. 5–8).

3.1. Section A

The arbitrary seismic line crosses the area south of the Rauchenwarth Plateau (Fig. 2) displaying a negative flower structure (Fig. 5). Miocene sediments (Karpatian to Pannonian) are faulted in a tulip structure with the two main faults 1 and 2 (Fig. 5). The western fault (main fault 1) splays into several branch faults in the upper part of the section between 0.25–1.5 s TWT imbricating the margin of fault block A (Fig. 5, 1.5–3.2 km). The main faults of the tulip structure converge into a common major strike-slip fault at about 2.7 s TWT (c. 4000 m depth). Growth strata within the tulip structure and stratigraphic thicknesses outside the fault zone constrain the timing of fault activity. Within the tulip all stratigraphic units show increased thickness compared to the bordering fault blocks A and C (Fig. 5). The Top-Lower Pannonian horizon is offset by up to 0.75 s TWT (c. 1000 m, using velocity information from wells for depth conversion) in the tulip structure, indicating major fault activity approximately between 10 and 7 Myrs (fault block B, Fig. 5). Growth strata geometry and the easterly tilt of strata suggest that dip-slip displacement along the south-eastern main fault 2 was higher than on main fault 1 in post Lower Pannonian times. In general, strata in fault block A and B dip to the east while block C displays sub-horizontal stratification.

3.2. Section B

The section is located approx. 7.5 km northeast of Section A and also depicts a negative flower structure (Fig. 6). It differs significantly from Section A with respect to the age of growth strata and the direction of tilting within the flower structure (fault block E). In Section B, the main sedimentary thickness variation occurs across the fault system of fault 3 bordering the flower structure to the east. Maximum throw on this fault system for the Top Karpatian horizon is 0.8 s TWT.
(c. 1250 m). Badenian and Sarmatian growth strata accommodate a large portion of normal fault offset. While Badenian and Sarmatian thicknesses do not change significantly across the fault system bordering the flower structure to the west (main fault 1), Pannonian and younger sediments display their maximum thickness here. The changing polarity of growth strata indicates a shift of main dip-slip fault activity from the eastern (main fault 3) to the western fault (main fault 1) in the Pannonian. Unlike in Section A, all Miocene reflectors dip to the west.

### 3.3. Section C

This northeast-striking inline of the 3-D block parallels the scarp of the Rauchenwarth Plateau (Fig. 7, for location refer to Fig. 2). The south-western part of the section displays relatively thin Miocene sediments (1.25 s TWT, c. 1400 m) overlying a basement high, which is delimited by a major normal fault (main fault 4, Leopoldsdorf Fault; Fig. 1). The fault shows a throw of approx. 1 s TWT (1600 m) at the base of the Badenian and is characterized by large-scale rollover (Fig. 7). Growth strata in the hangingwall indicate that most of the normal fault activity occurred in the Badenian and decreased through the Sarmatian to Pannonian. Since Pannonian times at least 0.3 s TWT (c. 300 m) of throw along the fault is documented. This fault is one of the major normal faults forming the step-over geometry of the pull-apart basin (Fig. 1). The fault terminates against and branches off from the strike-slip fault (main fault 1), thus being delimited by the negative flower structure of Section A (Figs. 5 and 8b). Fault geometries depicted in 3-D seismic and the pre-Miocene basement topography indicate a kinematical linkage of both faults rather than a cross-cutting relation.

The northern part of the section comprises a fault system (main fault 5) forming the western limit of a negative flower structure (Fig. 7). Minor stratigraphic separations and thickness variations across the flower structure as well as the small reverse offsets of the Karpatian across main fault 5 indicate predominantly post-depositional activity and/or a high strike-slip component.
Fig. 3. (a) Shaded digital elevation model of the Vienna Basin south of Vienna and the Danube River. Illumination from 315/45. The white rectangle indicates position of 3-D seismic survey by OMV Austria. (b) Geological map (modified from Fuchs and Grill, 1984) draped over digital elevation model. Additional information: Isopach contours: thickness of Pleistocene fluvial gravels infilling the Mitterndorf Basin (below terrace base). For topographic information refer to Fig. 2, which shows the same area as Fig. 3a,b.
3.4. Map of reflected energy

Seismic attributes are used as additional technique to map faults in the 3-D survey and to spatially link the faults interpreted in sections. The attribute map shown in Fig. 8a provides an overview of the map distribution of fault zones based on the total energy reflected from an interval between 0.5 and 0.75 s TWT (c. 500–800 m depth). This interval has been chosen because it is relatively close to the surface and is relatively complete, with only few gaps in the seismic data caused by missing source or receiver points (cf. Sections A, B and C). Low amounts of reflected energy displayed in narrow linear zones of the attribute map are interpreted as fault zones with partly destroyed sub-horizontal layering. The destruction or small scale tilting of layering by faulting results in the loss of impedance changes within seismic resolution and/or reflection of energy away from receivers. The coincidence of faults mapped in the cross-sections with zones of low reflectance proves that this interpretation is correct for most of the survey apart from the north-eastern region, where low reflected energy is related to seismic acquisition and processing (i.e., only partial correction of static problems and/or missing overlap). Other geological reasons potentially causing zones of low reflectivity such as homogenous material without contrasting impedances or regionally tilted strata causing energy loss due to reflection and refraction away from receivers are ruled out for this dataset.

The seismic attribute map displays a fault pattern with a major NE-striking fault (segments of main fault

Fig. 4. Topographic sections across the Rauchenwarth Plateau, and the north-eastern depocenter of the Quaternary Mitterndorf Basin. The plateau shows a general westward tilt (schematically indicated) and is covered by slightly west-tilted Pleistocene terraces (T3, indicated by arrow). In contrast the younger terrace T2 to the east is not tilted. Vertical exaggeration is 100 (see Fig. 2 for location of transects).

Fig. 5. Section A. Seismic data and interpreted section from the 3-D reflection seismic survey Moosbrunn (data with courtesy of OMV, Austria) showing a negative flower structure dissecting both the pre-Miocene basement and Miocene sediments (see Fig. 2 for location). Vertical exaggeration is approx. 2.5 at 2 s TWT. The inset-map to the lower right represents the outline of the 3-D survey, displaying the position of the section (red line), the simplified main faults (numbered in circles 1–5) and main fault blocks (letters A–G, hatched), also indicated at top of the interpreted section.
1, labelled 1a to 1d; Fig. 8) paralleling and underlying the morphological scarp of the Rauchenwarth Plateau. The fault forms the NW boundary of the negative flower structure mapped in Sections A and B. The faults 2 and 3 at the SE boundary of the flower structure as well as fault 5 are shown to splay off from the main fault 1 depicting a fault geometry indicative for divergent sinistral wrenching. The southernmost extension of the Leopoldsdorf normal fault (main fault 4) terminates at fault 1a of the main NE-striking strike-slip fault system.

4. Active tectonics inferred from Quaternary geology and geomorphology

The following section evaluates and summarizes data indicative for Quaternary and recent deformation in the area of the 3-D seismic survey and its vicinity. Morphological data, the thickness of Quaternary sediments, tilting of fluvial terraces, geodetic levelling indicating recent surface subsidence, and earthquake data are used to prove Quaternary to recent activity of individual faults.

4.1. Active faults around the Rauchenwarth Plateau

The Rauchenwarth Plateau south of the Danube (Fig. 2) is a triangular shaped elevated plateau with Pannonian strata rising up to 65 m over the Late Quaternary to recent fluvial deposits of the surrounding extremely flat part of the Vienna Basin (Fig. 3b). The plateau is characterized by a smooth and gently WNW-dipping surface, which is transitional to the flat part of the basin west of the plateau, and an erosive boundary facing the Danube in the north-east (Fig. 4). The south-eastern limit of the elevation is a pronounced scarp coinciding with the fault MF 1 mapped in 3-D seismic (Figs. 3a and 8b). The area below the scarp is covered by up to 150 m thick Quaternary fluvial deposits of the Mitterndorf Basin topped by historical swamps (cf. Decker and Peresson, 1998; Decker et al., 2005). The position of this Quaternary basin exactly on top of the centres of subsidence of the negative flower structure mapped from 3-D seismic, the recoded seismicity and available seismic fault plane solutions give evidence for the continued activity of the fault zone as a sinistral strike-slip system (Fig. 8b). All data therefore strongly suggest a tectonic origin of the south-eastern scarp of the Rauchenwarth Plateau. The
combination of 3-D seismic data with the digital elevation model shows that the fault scarp starts to rise at the branch point of the Leopoldsdorf Fault (main fault 4) splaying off from fault 1, which underlies the scarp further north (Figs. 1 and 8b). At this branch point the main apparent dip-slip displacement in the flower structure of the Mitterndorf Fault System transits from the south-eastern boundary fault (fault 2) to the north-western branch with fault 1b and 1c below the scarp (Figs. 5 and 6).

Additional information on Quaternary deformation of the Rauchenwarth Plateau comes from tilted fluvial terraces of the Danube overlying the northern slope of the plateau (Figs. 3b, 9 and 10). In topographic sections paralleling the Danube, the terrace T3 displays a slope gently dipping against the flow direction of the river (Figs. 9 and 10). Fossil vertebrates and molluscs constrain the age of the gravels as late Middle to Late Pleistocene (Küpper, 1954; Frank and Rabeder, 1997c). Recent westward tilting of the plateau is further...
corroborated by precise geodetic levelling showing up to 0.5 mm/yr subsidence for its western part (Fig. 9; Högerl, 1993).

The position of the tilted Rauchenwarth Plateau in the triangular shaped area between the Leopoldsdorf Fault and Mitterndorf Fault system indicates that the
4.2. Active faults north and south of the Rauchenwarth Plateau

In this paragraph, we consider the continuation of the active faults interpreted in the previous section in adjacent areas of the Vienna Basin. In order to do this, interpretations by Decker et al. (2005) and re-interpreted published data are taken into account. Results are summarized in a tectonic map of the southern Vienna Basin highlighting inferred active faults (Fig. 10).

The 3-D seismic data allow the mapping of the north-eastern continuation of the strike-slip fault system forming the fault scarp of the Rauchenwarth Plateau (main fault 1) into the area of the Arbesthal Hills beyond the north-eastern termination of the Mitterndorf Basin (fault 1d, Fig. 8b, line drawing of seismic Section D, Fig. 9, cf. Fig. 2 for location names). The fault strike at surface is marked by a north-east trending dry valley transecting the hilly upland (Figs. 3a and 8). Several north-striking branch faults dissect the northern part of the Rauchenwarth Plateau (Fig. 8b). The passage of the Fischa Creek between the Rauchenwarth Plateau and the Arbesthal Hills coincides with two minor branch faults seen in the seismic (parts of fault 5, Fig. 7, 8b and 9). Apart from the morphological expression, active faulting is indicated by marked relative subsidence of up to 1 mm/yr (Höggerl, 1993; Fig. 9) measured for the westernmost Arbesthal Hills, which correspond to fault block G between fault 5 and 1d (Fig. 8). Interestingly, the location of subsidence pattern is directly situated in along strike continuation of the Mitterndorf Basin depocenter, hence making a comparable flower structure kinematics likely. Both faults, 5 and 1d, are linked to active faults, which offset Pleistocene terraces and delimit thick Quaternary basins north of the Danube (Decker et al., 2005). Main fault 1 links to a north-east striking fault system, which is traced across the Lassee Basin into the Slovak part of the Vienna Basin. The north-striking branch faults (fault 5 and parallel faults) strike towards a group of curved faults offsetting Quaternary terraces and delimiting two other Quaternary basins (Fig. 10; see also Decker et al., 2005).

The south-western continuation of the strike-slip faults 1 and 2, which delimit the subsided Mitterndorf Basin, is traced for about 30 km to the south-western tip of the Vienna Basin. The boundary faults of the Mitterndorf Basin depicted in Fig. 10 have been interpreted from Quaternary thickness maps (Prohaska, 1983; Berger, 1987; Fig. 10, location point 4). A negative flower structure geometry similar to the 3-D seismic area is assumed for the southern part of the Mitterndorf Basin. To the southwest, the surface traces of the basin boundary faults converge into a narrow principle displacement zone, which has been shown to offset
Pleistocene gravels (Küpper, 1971; location 5 in Fig. 10). The fault is connected to the southwest striking seismically active Mur-Mürz Fault, which represents the southern part of the Vienna Basin Transfer Fault outside the Vienna Basin (Fig. 1). In map view the overall geometry of the Mitterndorf Basin resembles a rhomb between two major left-stepping north-east striking sinistral faults.
5. Active kinematics in the Vienna Basin

The mapping of active structures as demonstrated in the previous chapter shows a variety of faults, which show strong indications of recent activity.

As highlighted by Decker et al. (2005) the present kinematics of the Vienna Basin Transfer Fault mimics the Miocene kinematics: the sinistral fault system links divergent structures in the Eastern Alps with thin-skinned thrust systems in the Eastern Carpathians. As part of this fault system, the Vienna Basin represents a pull-apart structure within the former alpine thrust wedge (cf. Decker et al., 2005, their Figs. 2 and 5).

In order to enhance the understanding of the fault system in the Vienna Basin we will use the results gained so far to constrain a schematic kinematical model (Fig. 11). The model is subdivided into three domains (I–III; Fig. 11), which are also illustrated in sections.

I) The Vienna Basin Transfer Fault enters the Vienna Basin at its south-western tip as a narrow displacement zone (Mur-Mürz Fault) separating the extruding Styrian Wedge from the Alpine Thrust Units (Fig. 11, Section I). Seismicity along this sector is relatively high (Reinecker and Lenhardt, 1999; Hinsch and Decker, 2003).

II) Entering the southern Vienna Basin the strike-slip fault builds up a negative flower structure within the Miocene sedimentary basin fill, which increases in thickness towards the centre of the basin (Fig. 1). The faults delimit a rhomboidal pull-apart structure between a minor left-step of the strike-slip fault, which in cross-section appears as a negative flower structure developed in the uppermost sediments (Fig. 11, Section II). This rhomboidal negative flower structure is overlain by the Quaternary Mitterndorf Basin (Fig. 10). The branch line at which the basin boundary faults converge into a principal displacement is located close to the base of the Miocene sedimentary rocks (Figs. 5 and 6). Such upward branching of basement strike-slip faults entering into sedimentary layers is a common observation at interfaces of heterogeneous materials as shown by analogue modelling (Naylor et al., 1986; Richard et al., 1995).

III) A major kinematical boundary of the segmented fault system is represented by the branch line of the southernmost large normal fault spanning the pull-apart basin. The Leopoldsdorf Fault splaying from the strike-slip fault below the Mitterndorf Basin characterizes the beginning of this domain. Westward tilting of terraces and Pleistocene strata clearly demonstrate that a rollover associated with fault activity on the westernmost normal faults of the Vienna Basin is active (i.e. Leopoldsdorf fault and Steinberg fault; Fig. 1 Points 1 and 2; see also Decker et al., 2005, their Figs. 5 and 9). Additional normal faults branch from the SW–NE trending strike-slip fault zone to its northern side (displayed Fig. 11, Section III). These additional faults cause only minor stratigraphic separation within the Miocene strata as displayed in the 3-D seismic data (Fig. 7) but dissect and tilt Quaternary terraces close to and north of the Danube (Figs. 9, 10 and Decker et al., 2004, their Fig. 9). Splay faults are connected to the principal displacement zone either directly or via the Miocene pull-apart detachment, which is commonly interpreted to coincide with the decollement of the Alpine–Carpathian thrust system (Royden et al., 1983;
Within the sedimentary cover and the upper parts of the crust the active fault system in the Vienna Basin thus successively splits up into an increasing number of branch faults in the basin centre. Active movements on the fault system thus need to be partitioned on these faults. This is schematically shown in Fig. 11 by the thickness of the fault traces. Detailed quantification of this strain partitioning, however, is extremely difficult and Fig. 11 shows a crude estimate based on observations like quaternary gravel thickness and tilting of terraces. We assume that movement on the fault system concentrates along the trend of the deep Quaternary basins (Mitterndorf and Lassee Basin, Fig. 10). These basins line up with earthquake epicentres along the Vienna Basin Transfer Fault (Fig. 1) favouring the interpretation that the fault system now does not have a pull-apart step-over geometry but a more or less straight north-eastern continuation into the Western Carpathians. Thus, the active normal faults within the basin do not seem to act as faults of a large-scale pull-apart basin, as they did in the Miocene. Their reactivation rather is kinematically linked to the more or less straight sinistral strike-slip fault zone at the south-eastern border of the Vienna Basin. Accordingly, recent pull-apart formation affecting the whole Vienna Basin is unlikely. This change from pull-apart to a linear transfer geometry likely corresponds to the observed regional change of tectonics in Pliocene times in the whole Pannonian domain from extensional basin formation to compressional inversion (Horváth and Cloetingh, 1996). However, more neotectonic data from the northern Vienna Basin is necessary to clarify this.

The presented model is in good agreement with regional kinematic constraints. One of the latest felt earthquakes occurred on a principal fault zone below the Mitterndorf Basin (ZAMG, 2001; Ebreichsdorf, three events recorded on 12 July 2000 with magnitudes between 3.0 and 4.0, for location compare Fig. 2). The suspected main fault zone is part of the large-scale strike-slip transfer fault at the south-eastern border of the Vienna Basin. The focal solution of the strongest event is interpreted as sinistral strike-slip on a north-east striking plane (Fig. 8b; Tóth et al., 2000). A smaller earthquake from November 2001 can be attributed to the splaying normal faults. The focal solution of this event is interpreted as a slightly oblique normal fault (Fig. 8b; Tóth et al., 2001).

On a more regional scale the model of the transfer fault system is in good agreement with GPS observations revealing c. 2 mm/yr NE-directed movement of the Styrian Wedge with respect to the European foreland (Grenerczy et al., 2000). It also agrees with most of the maximum horizontal stress directions presented in Reinecker and Lenhardt (1999, their Fig. 8). However, one of their stress indicators within the Vienna Basin depicts E–W oriented maximum horizontal stress, which is in contrast to the sinistral kinematics proposed here. On the other side, this stress data contradicts breakout measurements indicating NNE–SSE directed maximum horizontal stress by Marsch et al. (1990), which supports our interpretation.

6. Conclusions

Mapping of active faults in the Vienna Basin reveals a highly segmented system of strike-slip and normal faults. The major strike-slip fault zone is traced along the south-eastern border of the Vienna Basin by mapping subsided Quaternary basins and surficial fault scarps, which overly negative flower structures. Active faults form a zone of en-echelon faults, which is up to 10 km wide at surface. According to reflection seismic data, these faults merge into a principal fault zone below 4–5 km depth.

Active strike-slip faulting is kinematically linked to the reactivation of major Miocene normal faults branching off from the wrench fault in the central Vienna Basin. Their recent activity is proven by tilted fluvial terraces and offset Quaternary sediments. Within the Vienna Basin, both the normal faults and the strike-slip system are thought to root on the former floor thrust of the Alpine wedge. This decollement surface is situated in depth between c. 4 and 15 km, thus in depth of seismic activity.

Fault segmentation is one of the important input parameters of seismic hazard evaluations (e.g., Schwarz and Coppersmith, 1984) and information on the seismogenic fault segmentation might be assessed from near surface geological data (Cowie and Scholz, 1992; Stewart and Taylor, 1996). Assessments of the seismogenic segmentation of the Vienna Basin Transfer Fault Zone would provide important constraints for maximum credible earthquake (MCE) calculations. From a kinematical point of view, the branch line of the Leopoldsdorf Fault represent a fault segment border which is likely to subdivide the fault also at seismogenic depth. At this branch line at least some of the movement of the fault system must be transferred to the dipping basal detachment, distributing strain throughout the Vienna Basin. Apart from that, we think that it is highly problematic to map seismogenic segments for the strike-slip fault system at the south-eastern border of the Vienna Basin from fault segments mapped in the upper 4 km. Too many reactivated faults from the Miocene are acting as branch or splay faults to define valid segment boundaries for the main fault system. High resolution seismological investigations are needed to further
constrain fault segmentation in depth below 4–5 km. Additional mechanical modelling of the fault system might allow a more quantitative assessment of the deformation partitioning occurring on the branch faults and hence helps to understand the relationship between the field kinematics, seismic and aseismic deformation in the Vienna Basin.

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