Characterizing Active Faults in the Urban Area of Vienna

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Abstract: *The identification of active faults that lie beneath a city is of key importance for seismic hazard assessment. Fault mapping and characterization in built-up areas with strong anthropogenic overprint is, however, a challenging task. Our study of Quaternary faults in the city of Vienna starts from the re-assessment of a borehole database of the municipality and geological descriptions of historical outcrops. The latter were found to be particularly valuable by providing unprejudiced descriptions of Quaternary faults. Data provides evidence for several active normal faults that are part of a fault system compensating fault-normal extension at a releasing bend of the Vienna Basin Transfer Fault. Slip rates estimated for the urban faults are in the range of several hundredths of millimetres per year matching the slip rates of normal faults that were trenched outside the city. Fault dimensions of the faults suggest that they are capable of producing earthquakes with M>6.*

Key words*: active fault, fault slip rate, paleoseismology, seismic hazard, Vienna.*

INTRODUCTION

The city of Vienna is located about 20 km NW of the Vienna Basin Transfer Fault (VBTF), an active sinistral strike-slip fault which moves with a velocity of about 1 to 2 mm/a (Decker et al., 2005). It has been shown that the strike-slip fault is kinematically linked to a series of active normal faults that accommodate fault-normal extension at two large-scale releasing bends (Figure 1). These faults branch from the strike-slip fault at knickpoints where the fault strike changes by angles of 20°–35°. The normal faults merge with the strike-slip fault at a common detachment which is thought to coincide with the Alpine-Karpathian floor thrust at about 8 to 12 km depth (Beidinger & Decker, 2012). The detachment dips with about 5-10° to SE. This topography results in a strong asymmetry of the normal faults with respect to the strike slip fault. All major branch faults extend to the N and NW of the strike-slip fault, i.e., towards and into the city of Vienna.

Historical seismicity (Imax/Mmax = 8/5.2) in the Vienna Basin is moderate and exclusively focused along the NNE-SSW striking left-lateral strike-slip VBTF that delimits the basin towards the east. The normal splay faults seem to have been seismically inactive during historic times (the oldest earthquake records from the Vienna Basin date to the 18th century; Nasir et al., 2013). Paleoseismological data, however, proves that both types of faults, the strike-slip system and the normal branch faults are capable of releasing strong earthquakes with magnitudes up to M~7 (Hintersberger et al., in press; Hintersberger et al., 2013). In spite of the apparent seismic potential of the normal faults and the importance of fault parameters for seismic hazard analyses an attempt to identify and characterize active faults in the built-up area of Vienna has so far not been undertaken.

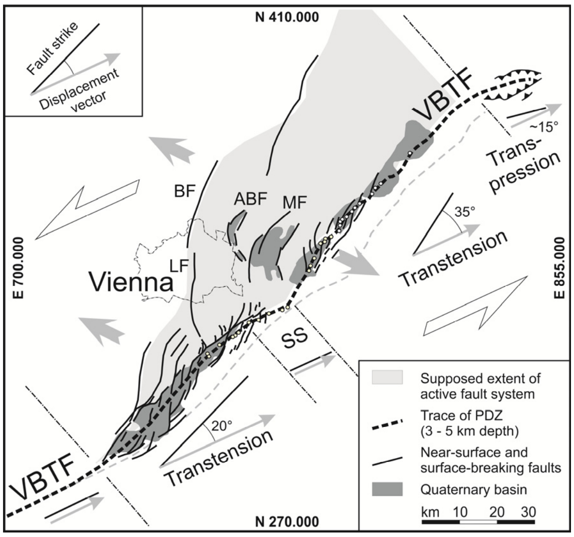

Figure 1: Active faults in the Vienna Basin. VBTF: sinistral strike-slip faults of the Vienna Basin Transfer Fault System; note the two transtensional releasing bends. Normal branch faults: LF: Leopoldsdorf fault; BF: Bisamberg fault; ABF: Aderklaa-Bockfließ fault; MF: Markgrafneusiedl fault. SS: non-transtensive strike-slip segment.

DATABASE

Our approach to map Quaternary faults in an urban area uses the following data: (1) Miocene fault maps based on drillings and geophysical data that were collected for deep ground water and hydrocarbon exploration. (2) A database of several tens of thousands of shallow boreholes maintained by the City of Vienna. These data proved extremely valuable for mapping the base of the Pleistocene river terraces of the Danube and establishing isopach maps of Quaternary sediment thickness. Data allows identifying Quaternary faults by the offset of terraces or the existence of Quaternary growth strata. (3) Historical outcrop documentations of sandpits and construction pits that were excavated in the 19th and 20th century in today's built area. (4) Digital elevation data including Lidar. (5) Vertical ground displacement measured by two radar interferometry campaigns (ERS 1995-2000 and ENVISAT 2002-2010). The random noise in the data and strong anthropogenic effects, however, did not allow for a tectonic interpretation of this data.

QUATERNARY FAULTS IN THE URBAN AREA

The Quaternary faults extending into the city limits of Vienna are part of the E-dipping Leopoldsdorf normal fault system that branches from the VBTF 20 km south of Vienna (Figure 1). The fault formed as a Miocene growth fault and has a maximum cumulative vertical offset of about 3 km. It terminates towards N where extension is transferred via a left fault step to the Bisamberg normal fault system, another Miocene fault with c. 1 km throw. The stepover between the two systems is located within the urban area of Vienna.

Quaternary normal faulting at the Leopoldsdorf fault system is evident from the displacement of Late Pleistocene terraces of the Danube SE of Vienna and the tilting of the terraces by hangingwall rollover. The tilted terrace dips against the flow direction of the Danube.

Quaternary faulting is further proved by the displacement of late Middle Pleistocene loess and Late Pleistocene (Holocene?) gravels of the Danube, which were exposed in historical sandpits and construction pits in Vienna. Kümmel (1935) described E-directed normal faults with dip-slip slickenlines from such an historical outcrop in great detail noting the orientation of the fault plane, striation, and the alignment of elongated pebbles that parallel the fault plane and slickenline (location 1 in Figure 2). His description and biostratigraphic data by Frank & Rabeder (1997) prove that the exposed fault offsets late Middle Pleistocene loess (older than about 120 ky) for several meters suggesting a slip rate of a few hundredths of one millimetre per year for the formerly exposed normal fault.

Wiener Gewässermanagement (2011, 2014) published geological cross sections constructed from a dense network of shallow boreholes. The profiles show E-dipping normal faults offsetting Late Miocene sediments. Some of these faults coincide with terrace boundaries of two Pleistocene terraces in the South of Vienna (Figure 3). The ages of the terraces are not constrained by physical age data. The interpretation of fault controlled rather than erosional terrace boundaries is corroborated by the increase of the thickness of Quaternary sediments towards the faults which is indicative for rollover or flanking fold formation and growth strata deposition.

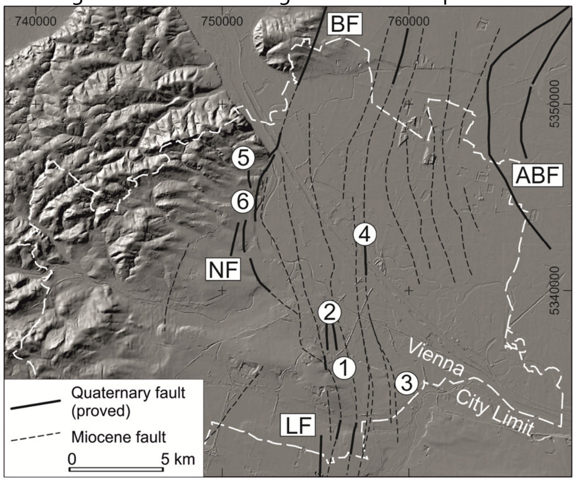

Figure 2: Quaternary faults in the city of Vienna. Evidence for Quaternary faulting at locations 1 to 6 is described in the text. LF: Leopoldsdorf fault; BF: Bisamberg fault; NF: Nussdorf fault; ABF: Aderklaa-Bockfließ fault.

E-dipping normal faults offsetting the fluvial gravels of the lowermost terrace of the Danube have further been exposed by drilling and excavation close to the Danube (Plachy, 1981; location 4 in Figure 2). A temporary construction pit exposed a normal fault that offsets the gravel of the terrace. The base of the Pleistocene sediments is described to be offset for about 2 m indicating a Late Pleistocene to (?) Holocene growth fault. Assuming a Wuermian age for the terrace gravel leads to an estimated normal displacement rate of a few hundredths of one millimetre per year which is comparable to the estimate derived from the observations described by Kümmel (1935).

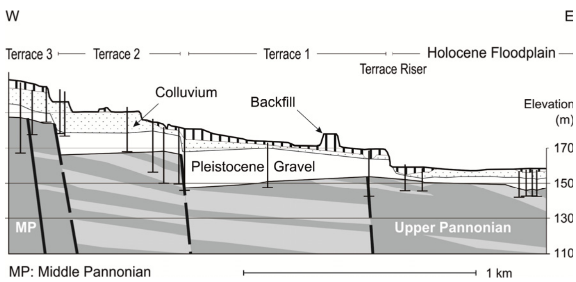

Figure 3: Splay faults of the Leopoldsdorf fault forming the boundaries of the undated Pleistocene terraces 1 to 3 in the South of the city of Vienna. Redrawn from Wiener Gewässermanagement (2014). Location 2 in Figure 2.

The Bisamberg and Nussdorf normal fault system forms the western boundary of the Vienna Basin within the city of Vienna and north of it. Quaternary normal faulting is indicated by the tilt of the Middle Pleistocene Gaenserndorf terrace E of Vienna which has been dated to 300 to 200 ky by OSL/IRSL age dating (Fig. 4; Hintersberger et al., in press). The terrace dips westwards towards the Bisamberg and Aderklaa-Bockfließ fault with a slope of about 0.005°. Tilting of the terrace against the gradient of the Danube must have occurred in the last 200 ky after the abandonment of the terrace. The amount of normal offset at the faults W of the terrace is estimated from a reconstruction of the paleo-surface. Restoring the original surface by back fitting the Quaternary fault offsets by a move-on-fault approach and back-tilting of the paleo-surface to the river gradient of the Danube suggests about 29 m cumulative normal offset at the Bisamberg and Aderklaa-Bockfließ fault which corresponds to a cumulative average slip rate of these faults of about 0.15 mm/y for the last 200 ky.

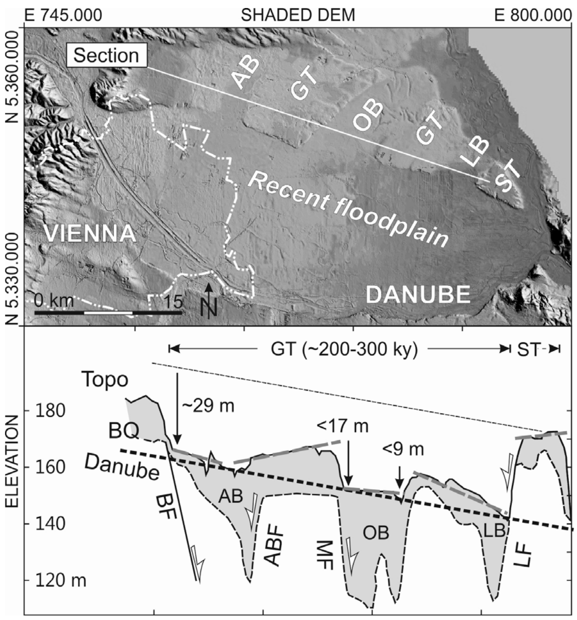

Figure 4: DEM of the floodplain of the Danube and the Middle Pleistocene Gänserndorf-Schlosshof terrace. The terrace is displaced by faults and tilted against the flow direction of the Danube. BF: Bisamberg fault; ABF: Aderklaa-Bockfließ fault; MF: Markgrafneusiedl fault; LF: Lassee fault; BQ: base of Quaternary; Quaternary basins: AB: Aderklaa basin; OB: Obersiebenbrunn basin; LB: Lassee basin. Redrawn from Decker et al. (2005).

The Nussdorf fault forms the southern continuation of the Bisamberg fault (Figure 2). It follows a morphological scarp between the lowermost Pleistocene terrace of the Danube and the foothills of the Wienerwald range. The Quaternary activity of several of its branch faults has been proved by historical outcrops in construction pits and sandpits which were exploited in the late 19th and 20th century. Faulted Quaternary sediments have been mapped by Fink et al. (1958; offset Pleistocene gravel and loess, Wien-Hohe Warte; location 5, Figure 2), Küpper et al. (1951), and Toula (1906; E-dipping normal faults in loess, Wien-Heiligenstadt; location 6, Figure 2). Toula (1906) provided an extensive description of E-directed normal faults offsetting a succession of "older" loess, which pre-date the deposition of a "younger" succession of loess and colluvial gravel suggesting a Pleistocene event horizon. Additional faults with smaller offsets are described to cut the youngest loess deposits. The southern continuation of the Nussdorf fault shown in Figure 2 is drawn according to data by Küpper (1951) who interpreted Quaternary growth faults in gravels of the Prater terrace from shallow boreholes. In addition, Plachy (1981) described E-dipping normal faults from Late Pleistocene terrace gravels which were exposed in construction pits close to the center of the city.

DISCUSSION AND CONCLUSIONS

The continuation and architecture of both, the Leopoldsdorf and Nussdorf-Bisamberg faults outside the city is well constrained by deep hydrocarbon exploration wells and reflection seismic. Data shows that both faults consist of a series of near-surface splay faults that merge downwards into a master fault. The surface breaking Quaternary faults identified in Vienna are regarded as parts of these splay faults. Data further constrains the fault length and fault areas of the master faults (Table 1).

Fault	Slip	Slip rate (mm/y)	Length (km)	Area (km²)	Mwmax
Bisamberg	normal	< 0.1 **	33	438	6.6-6.7
Leopoldsdorf	normal	< 0.05 *	33	685	6.7-6.8
Aderklaa-Bockfließ	normal	< 0.1 **	16	175	6.2
Markgrafneusiedl	normal	0.015-0.085	36	620	6.7-6.8

*Table 1: Fault parameters of active faults in Vienna. Slip rates: * estimates for single splay faults; ** estimated cumulative rate of Bisamberg and Aderklaa-Bockfließ fault: 0.15 mm/y. Mwmax: maximum magnitude estimated from fault parameters according to Wells & Coppersmith (1994).*

Due to the location of the faults in the city investigations by trenching are not feasible. A preliminary and speculative assessment of their seismotectonic characteristics may be obtained from a comparison to the Aderklaa-Bockfließ and the Markrafneusiedl normal fault (Figure 1). Both faults were investigated by trenching (Hintersberger et al., in press). Analogies exist with respect to fault orientation, kinematics, fault dimensions, age, kinematic linkage to the releasing bends of the VBTF, wall rock rheology, fault history, and slip rates. For the Markrafneusiedl fault, trenching revealed five Late Pleistocene surface-breaking paleoearthquakes with magnitudes between M=6.3 and M=7.0 and an average recurrence time of 20 to 25 ky. The magnitudes and recurrence intervals are in line with the fault dimensions and the average fault slip rate of about 0.015 to 0.085 mm/y which were established from geomorphic data and trenching. The latest events at the Markrafneusiedl and Aderklaa-Bockfließ fault occurred between 13-14 ky and after about 15-16 ky, respectively.

Our data from the urban area of Vienna and the comparison of the identified Quaternary faults clearly indicates that both, the Bisamberg-Nussdorf and Leopoldsdorf fault system have significant seismic potential and may release earthquakes with M>6 at large recurrence intervals. Both faults may therefore not be disregarded in seismic hazard assessment.

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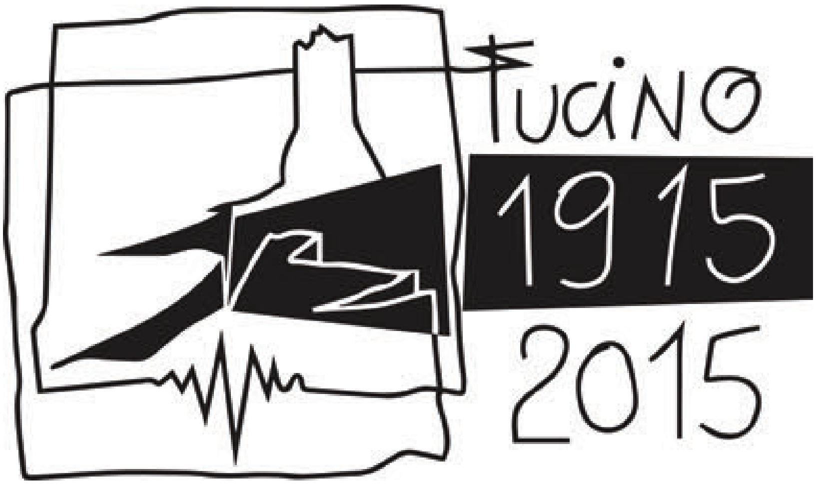

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