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Geostatistical analysis of elevation and lithology of Quaternary terraces in Vienna (Austria)

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Abstract

Within the city of Vienna, Quaternary terraces are dominant features of landscape morphology. They cover approximately 60% of the city area and the lowest two of the six levels constitute an important groundwater body. A wealth of data on terrace thickness and internal composition exists in the form of borehole logs in city archives. Geostatistical processing of this data was carried out on one hand to describe top and base elevations of Quaternary gravel units, and on the other hand to characterise the lithology of each terrace including regional trends. The morphologies of terrace base surfaces display the effects of tectonic faulting as well as the evolution of gradients and basin shape of the ancient Danube river during the Quaternary. The grain-size lithological compositions of the different terraces clearly mark a trend from older deposits containing more fine-grained material to younger ones with coarser-grained sediments. The results represent a geostatistically derived, quantitative description of Quaternary sediments for the whole of Vienna's city area.

Die Morphologie des Wiener Stadtgebietes ist von quartären Terrassen geprägt. Diese Terrassen bedecken ungefähr 60% der Fläche und die tiefsten zwei der insgesamt sechs Niveaus stellen einen bedeutenden Grundwasserkörper dar. Ein Reichtum an Daten hinsichtlich Mächtigkeit und Schichtaufbau existiert in Form von Bohrprofilen in den Archiven der Wiener Stadtverwaltung. Diese Daten wurden geostatistisch ausgewertet, um einerseits Ober- und Unterkanten der Terrassen zu beschreiben, andererseits um den lithologischen Aufbau inklusive regionaler Trends innerhalb der Terrassen zu charakterisieren. Die Morphologie der Terrassenunterkanten zeigt die Folgen tektonischer Abschiebungen sowie die zeitliche Entwicklung von Form und Gefälle des Talbodens der Donau während des Quartärs. Der korngrößenbedingte lithologische Aufbau der Terrassen zeigt einen deutlichen Trend von älteren Sedimenten mit höherem Feinanteil hin zu jüngeren, grobkörnigeren Ablagerungen. Die Ergebnisse liefern eine geostatistisch abgeleitete, quantitative Beschreibung der quartären Sedimente des gesamten Wiener Stadtgebietes.

1. Introduction and Geological Setting

The city of Vienna is situated at the western margin of the Vienna Basin, a pull-apart structure which formed during the Miocene due to lateral extrusion and tectonic movements between the Eastern Alps and the Western Carpathians (Decker et al., 2005). Marine to lacustrine sediments were deposited in the basin until the Upper Miocene (Pannonian), resulting in successions of several kilometres thickness. At the end of the Pliocene, a new sedimentation phase began. The braided Danube river entered the basin north of Vienna and started to deposit a succession of gravel terraces which characterise today's landscape morphology (Fig. 1). The climate-controlled process of terrace build-up and erosion lasted until the onset of the Holocene when the Danube changed to a meandering river system depositing the most recent gravel unit (van Husen, 2000).

The Quaternary terraces in the city area have long been the subject of geological investigation. Schaffer (1904), Fink and Majdan (1954) and Küpper (1968) established a widely used nomenclature for Viennese terraces and distinguished six units at different levels of altitude. Their results were based on natural outcrops, excavations and sparse borehole data. Brix (1970) summarized the findings of these investigations, giving an overview on the stratigraphy, lithology and altimetry of tops and bases, of the different gravel units. Subsequently, numerous projects aimed at mapping the Viennese terraces based on the geological interpretation of an ever-increasing number of borehole logs archived by the city administration (e.g. Janoschek, 1970; Plachy et al., 1984; Lebeth et al., 1988; Hofmann and Pfleiderer, 2003). A lot more studies exist as unpublished documents prepared by private consulting companies mostly covering small areas of Vienna in great detail. However, none of these studies focuses on a statistically derived quantitative description of Quaternary gravel units for the complete city area. The rapidly growing amount of borehole data calls for such a description and the first part of the present paper therefore aims at using altimetry data contained in borehole logs to describe the gravel deposits based on geostatistical analysis (see Pfleiderer, 2008).

The second part of this paper focuses on the grain size (lithological) composition of terraces. Early studies (Küpper, 1955) as well as recent publications (Schnabel, 1997; Grupe and Jawecki, 2004) have recognized that the distinction between terraces by altimetry alone becomes problematic in the presence of tectonic or gravitational movements. Whether sediments at a given elevation belong to the corresponding terrace or to an older, originally higher terrace which was moved downwards after deposition, can be determined more reliably by combining altimetry and grain size data. Therefore, cumulative statistics of sand, silt and clay layers within gravel sequences are calculated to derive a typical grain-size-related lithology of Quaternary terraces for Vienna's city area and to describe regional trends along the course of deposition.

2. Statistical description of terrace elevation

To describe the elevation of upper and lower limits (tops and bases) of Viennese Quaternary terraces, 9,439 borehole logs were scanned for surficial gravel layers, possibly covered by a fine-grained surface layer of loess or loam, and underlain by silt or clay (Neogene). The borehole logs represent a subset of over 52,000 logs stored digitally in the archives of the city administration (www.wien.gv.at/verkehr/grundbau/kataster.html). The processing of borehole data was performed semi-automatically in a GIS environment using a special tool developed for borehole data interpretation (Reitner, 2000). In regions where Neogene sediments are coarse-grained, and in areas where terraces are subdivided by a middle layer of colluvial silt (Grupe and Jawecki, 2004), the detection of terrace gravel units requires careful geological interpretation of logs and supervised identification needs to replace automatic processing.

Using a recently updated geological map of Vienna (Hofmann and Pfleiderer, 2003), the boreholes were grouped according to their location as belonging to one of six Quaternary units (Fig. 1). Of the total of 9,439 boreholes, 5,610 lie within the Meander zone, 957 on the Prater terrace, 806 on the Stadt terrace, 1,024 on the Arsenal terrace, 448 on the Wienerberg terrace and 594 on the Laaerberg terrace. For each group of boreholes, the elevations of gravel top and base were then analysed statistically and medians visualised in a schematic cross section (Fig. 2, modified after Pfleiderer, 2008).

In the Northeast, the two youngest units represent the Pleistocene Prater terrace gravel, and the Meander zone deposited by the Danube during the Holocene. The surface of these units cannot be distinguished statistically since both data sets have coinciding means, quantiles and ranges. This coincidence is confirmed by the morphology of the terrain which today shows virtually no step in altitude at the transition between Holocene gravel and Prater terrace gravel. In fact, as there is no difference in grain size and material either, distinguishing between the two units in the field relies on the type of soil overlying the gravel. Prater terrace sediments are covered by black earth (chernozem) while Holocene gravel is overlain by flood plain soil (fluvisol) (Schwarzecker, 1975). Base elevation data however differ between the two units (Fig. 2). Non-parametric median tests (Rock, 1988) reveal a statistically significant difference whereby the gravel base within the extents of the Meander zone is higher than the base of the Prater terrace. Instead of cutting deeper into older Pleistocene units, the Danube in the Vienna region apparently had a higher base level during the Holocene than at the end of the Pleistocene, as already described generally for regions along the Danube river (van Husen, 2000). By consequence, the lower end of the gravel sequence within the Meander zone possibly includes material deposited at the stage of the Prater terrace (Fig. 2).

Further Southwest, the four older terraces (Stadt, Arsenal, Wienerberg, and Laaerberg) can be clearly distinguished (Fig. 2) and for the Stadt and Arsenal terraces, elevations agree well with figures published by Fink and Majdan (1954), Küpper (1968) and Fuchs (1985). However, for the two oldest units, the upper and lower limits show somewhat lower elevations than those reported by former authors. Furthermore, data of these units display noticeably bimodal distributions which cannot easily be explained by the sedimentary processes of terrace build-up but may instead indicate subsequent vertical displacement. Post-depositional movement of terraces in the Vienna region is described by Schnabel (1997) as being caused by gravitational sliding and by Peresson (2006) as resulting from neotectonic activity. For the Laaerberg terrace, regional analysis shows the bimodal distribution to be due both to tectonic down-throw along normal faults at the eastern margin of Laaerberg, and to gravitational movement down the eastern slope of a hill top (Schmelz). Disregarding

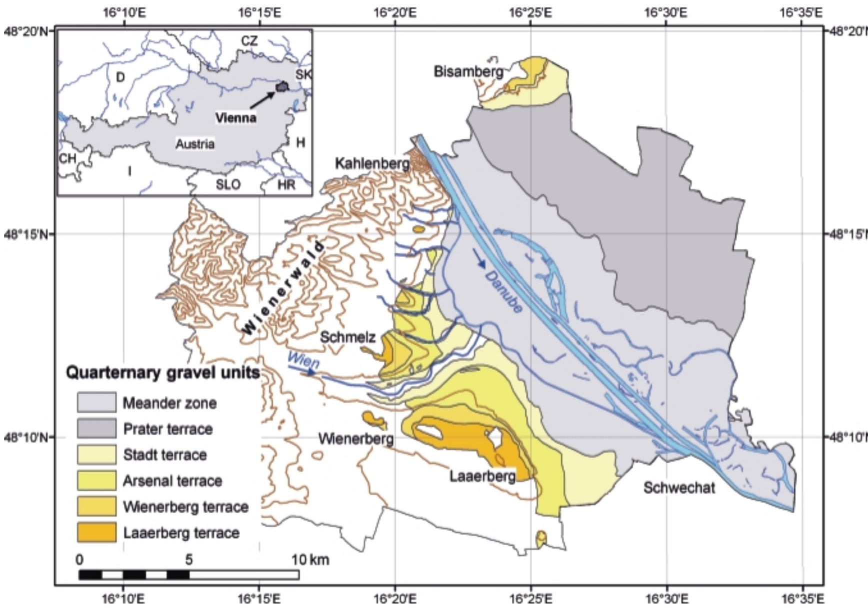

Figure 1: Location of study area and distribution of Quaternary gravel units in Vienna. Fine-grained surface layer (loess, loam) removed.

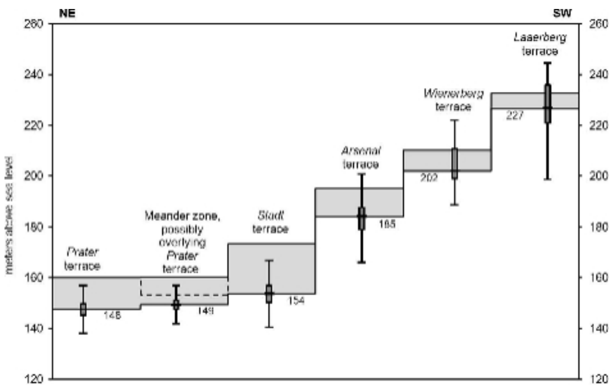

Figure 2: Medians of top and base elevation of gravel units across Vienna. Box-and-whiskers plots show statistical distributions (min, q25, median, q75 and max) of base altitudes. Numbers represent median values of base altitudes, dotted line indicates possible superposition of Meander zone over Prater terrace (partly modified after Pfleiderer, 2008).

these two areas of post-depositional movement results in the remaining elevation data being normally distributed around a mean which is close to the published numbers. With respect to the Wienerberg terrace, explanation for the bimodal distribution remains inconclusive. Possibly, Neogene gravel was falsely identified as Pleistocene terrace gravel in the area of Wienerberg, where unusually high elevation data are located.

The difference between median top and base elevation represents a measure of thickness for each gravel deposit. Comparing the six units in Figure 2 shows thicknesses increasing from older to younger terraces up to the Stadt terrace, which reaches a median thickness of 16.2 m. Values then decrease again for the younger units (Prater terrace and Meander zone). This reflects a trend in scouring and depositional energy which increased during the Pleistocene up to the Riß Stadial and later slowed down again, as shown by the evolution of river gradients discussed in the following chapters.

3. Spatial distribution of terrace elevation

Naturally, upper and lower limits of terraces display a slope along the direction of ancient river flow. Therefore, data were analysed regionally as well as statistically. Figure 3 demonstrates the downward trends from Northwest to Southeast for base elevation data of the three youngest gravel units. Constant gradients are calculated by median regression in Figure 3 (see also Pfleiderer, 2008). The inclinations amount to 1.5 ‰ for the Stadt terrace (blue line and markers) and 0.8-0.9 ‰ for the Prater terrace (pink line and markers) and the Meander zone (green line and markers). Top elevations of these terraces follow similar trends. The fact that gradients decrease from the Late Pleistocene to the Holocene has been reported for gravel deposits elsewhere in Austria (Winkler-Hermaden, 1955) and may ultimately be related to the tectonic uplift of the Alps (Kohl, 2000) or the subsidence of associated tectonic basins. Tectonic uplift or subsidence directly control the gradient and energy of rivers, and the trend in thickness described above is linked to these processes. Unfortunately, this kind of spatial analysis cannot be performed on the older terraces in Vienna since most of their material was removed by subsequent erosion and the extents remaining today are too localised for deriving statistically meaningful gradients.

Towards the southern end of the city, a distinct region of very low gravel base elevations is present (dotted line in Fig. 3). This area (Schwechat) represents a tectonic depression east of a large normal fault system (Leopoldsdorf fault, Decker et al., 2005) which subsided throughout the Neogene (Kröll and Wessely, 1993). The elevation data of gravel units in Figure 3 demonstrate that this subsidence was equally active during the Quaternary. Even today, modern high precision levelling by the Austrian Federal Office for Metrology and Surveying detect negative changes in altitude in this region (Höggerl, 1993).

4. Modelling of terrace base morphology

In addition to the analysis of constant linear trends along the river course, the high number and density of borehole data in Vienna permit a higher-order polynomial trend analysis of terraces in three dimensions. Thus, the general morphology of the Danube valley floor can be modelled at various stages during the Quaternary. Figure 4 illustrates the result of 3-D trend modelling of base elevation data of the Stadt terrace. Modelling of trend surfaces was performed with the "Geostatistical analyst" tool in ArcGIS™, which calculates global polynomial trends of any predetermined order following the principle of squared deviation minimisation (Johnston et al., 2001; Davis, 2002). For simplicity, third order polynomial expansion was used.

The X/Y plane in Figure 4 shows the extent of Stadt terrace gravel (yellow areas) as well as the location of boreholes within this unit (brown markers). Today, the deposits are lined up predominantly along the western bank of the Danube river except for the Northern city limits where a small area remains on the eastern side. The Y/Z plane corresponds to a transect parallel to the river similar to the graph in Figure 3. While a constant gradient was calculated before, the blue line here represents the projection of a third-order polynomial fit to the data. It describes a trend which is slightly steeper in the North-West and becomes less inclined towards the South-East. This may be related to a change in the river course before deposition of the Stadt terrace (Riß). While the Danube river was previously flowing from due North, during the Mindel-Riß interglacial it cut through the mountains of Kahlenberg and Bisamberg (Blühberger and Häusler, 1995). Entering the Vienna Basin through the newly formed erosional gate between these mountains, the scouring energy of the river was highest just behind the gap and slowed down further into the basin.

The X/Z plane simulates a section across the Danube river basin at the time of deposition of the Stadt terrace gravel. A U-shaped trend becomes visible (green line in Fig. 4), the centre line of which coincides roughly with today's river course. Although the data are unfavourably distributed for global polynomial interpolation since most data points lie on the Western shore of the Danube river, the resulting shape appears credible. It must be stressed that the green line represents the result of a 3-D trend analysis and does not depict the real basin floor at the onset of Stadt terrace deposition in the way it would be constructed by connecting borehole logs along a cross-section. However, since the central part of the terrace has been removed by subsequent erosion, a cross-section constructed today can only present the actual basin floor and not show the situation at the beginning of the Riß Glacial.

Similar analysis for the Prater terrace data reveals that the centre line of the basin shifted approximately 5 km towards the East during the latest stage of the Pleistocene whereas for the Meander zone (Holocene) it shifts back to approach today's river course. The schematic cross-section of Figure 2 supports this result. Judging from the width of other Danube-related basins further upstream (e.g. Tulln basin, Machland basin, see e.g. Schnabel et al., 2002), lateral shifts of this order of magnitude are not uncommon for the Danube river. Furthermore, the U-shape of the fitted polynomial surface in the X/Z plane is less pronounced for Prater terrace data and almost flat for the youngest gravel deposits. Along the river course (Y/Z plane), the two younger units show constant gradients and third order polynomial fitting does not reveal more detail as compared to the median regressions shown in Figure 3. However, to deduce real, rather than modelled, changes in basin shape during the Quaternary will require further research in addition to the trend analysis performed here.

5. Grain size lithological composition of terraces

In addition to elevation data, the borehole logs contain material descriptions of terrace gravel which hold geological information such as grain size and lithological composition of major and minor constituents, colour, as well as occasional details on grain shape, weathering, or other physical properties such as packing density, water content or porosity. Usually, terraces do not only consist of gravel but contain varying amounts of sand, silt or even clay in the form of intercalations of cm or dm thickness. Using the above mentioned grouping of boreholes according to geological units, the contribution of these fine-grained intercalations to the gravel sequences can be described quantitatively. The bar chart in Figure 5 shows the relative cumulative thickness of sand, silt and clay layers within the six gravel units. For each unit, data were derived by summing up log meters for ten categories of main, grain-size derived lithology (sandy and pure gravel; silty, gravelly or pure sand; clayey, sandy or pure silt; silty or pure clay) and by presenting the sums as percentages of the total. The 957 boreholes in the Prater terrace for example, cut through a total of 8,211 log meters, 6,261 m (or 76%) of which consist of sandy gravel. Only major constituents were considered for this calculation. It is stressed that the bars in Figure 5 do not represent the grain size distribution of a typical sample but rather the typical amount of finer grained intercalations to be expected when drilling through a gravel sequence.

A clear trend shows older gravel units comprising more sand and silt intercalations whereas younger deposits are predominantly made of sandy or pure gravel (Fig. 5, after Pfleiderer and Hofmann, 2007). The increase in river gradient and energy mentioned previously is suspected to lead to this trend as it causes the percentage of fine-grained sediments to decrease. During the Holocene, establishment of a meandering river system again leads to a slight increase of sand and silt intercalations in the Meander zone.

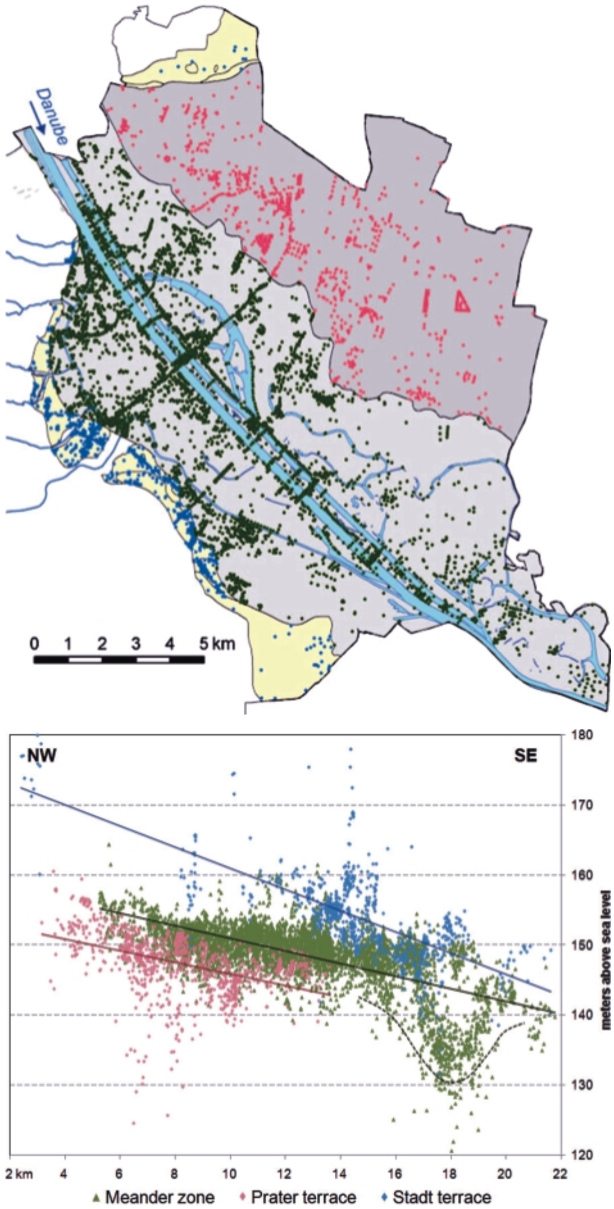

Figure 3: Trends of base elevation for the three youngest gravel units along the direction of ancient river flow (bottom). Location of boreholes used for analysis (top). Downward gradients amount to 1.5 ‰ for the Stadt terrace and 0.8-0.9 ‰ for the Prater terrace and the Meander zone. Dotted line indicates area of tectonic subsidence (Schwechat). (modified after Pfleiderer, 2008).

5.1. Spatial trend in lithological compositions

Rather than looking at bulk material composition, the borehole logs also permit to analyse the regional distribution of

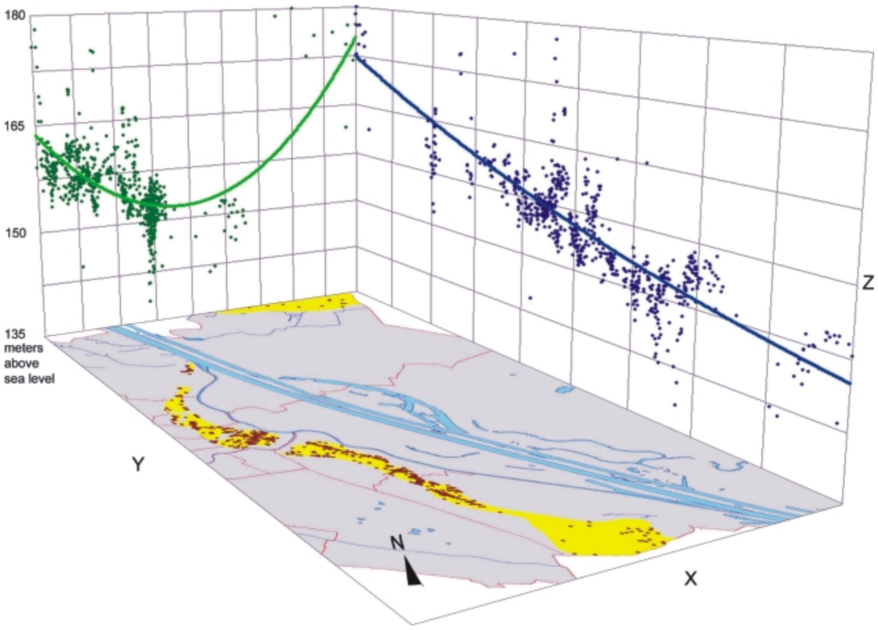

FIGURE 4: Three-dimensional trend analysis of base elevation data of the Stadt terrace. Yellow areas mark the extent of the terrace, brown markers depict boreholes. Blue and green lines represent projections of third-order polynomial fits to elevation data along the river and across it, respectively.

sandy or silty parts within a gravel unit. For this analysis, a map where boreholes are coloured according to the percentage of e.g. silt occurring over the length of the log, can be expected to reveal trends such as an increase in fine-grained material towards more distant parts of the accumulated body or towards the margins of the river basin. However, when plotting such borehole maps, no regional trends become apparent within any unit and geostatistical trend analysis provides no further clues that they exist in Quaternary deposits within the city limits of Vienna. Within the short distances of approximately 20 km along and 5 km across the deposits, the material apparently remained well mixed during transport and was homogeneously deposited by the river.

One noticeable exception to the otherwise uniform regional distribution of material composition represents a sudden increase in the amount of sand intercalations appearing South of the confluence of the river Wien and the Danube. Sandy material originating from the Wienerwald area (west of Vienna) is carried by this tributary into the basin and mixes with the sediment load of the Danube river. Increased sand intercalations downstream of this confluence are slightly noticeable in the Laaerberg terrace, more distinct in the Wienerberg terrace and most pronounced in the Arsenal and Stadt terraces. The two youngest units (Prater terrace and Meander zone) which contain very few sand intercalations, do not show this effect. While the contribution of platy gravel (Plattelschotter) to Vienna terraces from the Flysch sandstones of the Wienerwald is well known all along the western margin of the basin (e.g. Brix, 1970), here, the particular influence of the river Wien on lithological composition of gravel units during the Quaternary is demonstrated by intercalations of sandy layers concentrated South of the confluence of the Wien and Danube rivers.

6. Conclusions

The geostatistical analysis of Quaternary gravel deposits in Vienna was carried out to describe elevation and lithological composition on the basis of a high amount of data (9,439 boreholes in total). The statistical approach has the advantage to minimise both the effects of occasionally false log descriptions by drilling companies, and of data errors concerning altimetry or borehole location.

Elevation data were used to substantiate earlier altimetric classifications of terraces and to draw conclusions on changes in river gradient and basin shape with time, on the evolution of tectonic uplift and subsidence or on post-depositional vertical displacements. The altitudes of base levels of the Wienerberg, Arsenal, Stadt and Prater terraces and of the Meander zone agree with previously published numbers, while the bimodal distribution of Laaerberg terrace data provides evidence for tectonic or gravitational movements after deposition. The median thickness of gravel units increases from older to younger terraces (Laa-

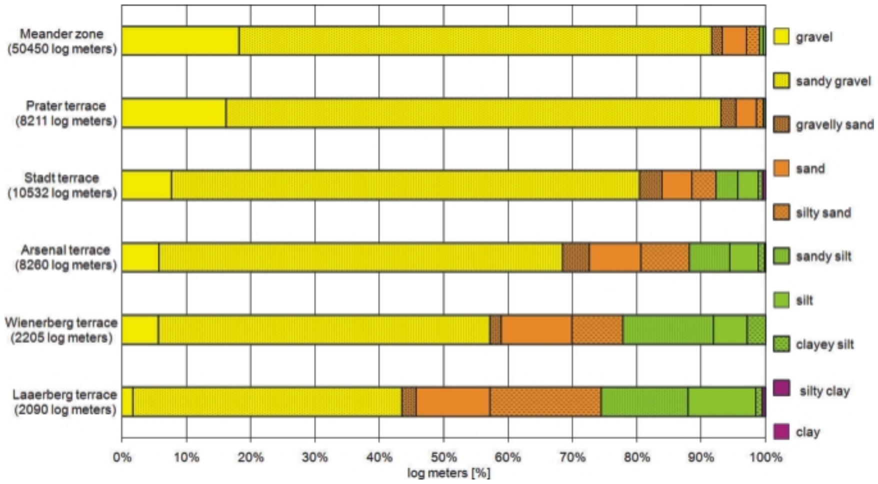

FIGURE 5: Cumulative thickness of gravel, sand, silt and clay layers within Quaternary units (modified after Pfleiderer and Hofmann, 2007).

erberg and Wienerberg terrace: 4.3 m, Arsenal terrace: 9.3 m, Stadt terrace: 16.2 m), then decreases again for the youngest units (Prater terrace: 12 m, Meander zone: 11 m). Constant gradients of terrace base levels amount to 1.5 ‰ inclination for the Stadt terrace and 0.8-0.9 ‰ for the Prater terrace and the Meander zone. 3-D trend analysis of the Stadt terrace gravel base shows a U-shaped Danube river basin at the time of deposition. The centre line of this basin coincides roughly with today's river course.

Grain-size lithological data were used to corroborate these conclusions and to statistically describe general trends as well as inhomogeneities in material composition. Quantification of the percentage of fine-grained intercalations within gravel sequences demonstrates a clear trend from older gravel units which comprise up to 50 % sand and silt layers, to younger deposits made of over 90 % sandy and pure gravel. Regionally, most of these sand and silt layers are distributed homogeneously. One exception exists south of the confluence of the Wien and Danube rivers, where sandy material is carried from the Wienerwald area west of Vienna into the basin resulting in an increase of sand intercalations within gravel units.

Although the spatial distribution of boreholes occasionally limits the possibilities of data interpretation, the study represents a significant statistical confirmation of previous findings and extends their level of detail. The more general conclusions of this paper contribute to the geological understanding of the Vienna region and additionally have important implications for applied fields such as hydrogeology, geo-engineering or raw materials research.

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