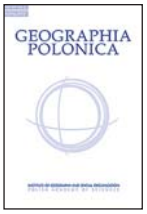

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RECONSTRUCTION OF THE MORPHOLOGY AND HYDROGRAPHY OF THE CENTRE OF KRAKÓW BEFORE THE MID-13TH CENTURY

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Abstract

The paper concerns investigations on urban geomorphology. The subject of the paper is the historic centre of Kraków (or Cracow) where the pre-human relief became masked due to the rapid increase in cultural deposits from the mid-13th century onwards. The aim of the investigation is the reconstruction of the original topography, relief and hydrography of this area based on rich sources of materials in papers and non-published data on geology, geoengineering, archaeology, history, and also on maps and panoramic drawings of the town. A digital elevation model has been generated, which showed the topography of the study area in the period before the mid-13th century. Structural analysis, cross validation test and estimation by ordinary kriging method were carried out. The final cartographic work was prepared with the use of QGIS and Surfer software. The distribution of landforms in the study area in the mid-13th century is presented as a proposed variant of the geomorphological map prepared by the authors. The former relief was evaluated in terms of its potential for encouraging settlement.

Key words

pre-urban morphology • Kraków • Vistula • meandering river • limestone horst • Pleistocene terrace • Holocene floodplain • digital cartography • geostatistics • ordinary kriging

Introduction

There has been a rapid increase in the interest of geomorphologists in the change of relief in urban areas. This resulted in the establishment of the Working Group of Geomorphosites of the International Association of Geomorphologists (IAG) at the Eighth International Conference on Geomorphology held in Paris in 2013. The effect of this interest is a series of papers published in *Quaestiones Geographicae* (2017, v. 36, no. 3), concerning, among other issues, the relationship between geomorphology and urbanisation (Pica, Luberti, Vergari, Fredi, & Del Monte, 2017). Changes in a town`s relief, especially

in its oldest areas, are defined as overbuilding and flattening of the land surface as a result of the increase of anthropogenic (cultural) deposits or in association with river deposits, as well as the lowering of this surface as a result of groundworks (e.g. Brandolini, Faccini, Paliaga, & Piana, 2017; Dall`Aglio et al., 2017; Pica et al., 2017; Reynard, Pica, & Coratza, 2017; Zwoliński, Hildebrandt-Radke, Mazurek, & Makohonienko, 2017). Similar results of investigations are included in publications (Kaniecki, 2004, 2013; Molewski & Juśkiewicz, 2014; Molewski, 2015; Pröschel & Lehmkuhl, 2019) on the Old Town areas in Poznań and Toruń, Poland and in Aachen, Germany. In general, these investigations are still in the initial stages, which is why there are no summary elaborations prepared on the manner and rate of increase of cultural deposits in relation to the initial relief of the historic centres of towns, especially those with a long history.

The key factor in success in defining changes in the relief of the historic centres of towns is the determination of the initial relief of these areas, i.e. before the rapid increase in cultural deposits. Later, after the establishment of towns based on the Magdeburg law in Central Europe in the 13th and 14th centuries, considerable changes in each town`s relief occurred which masked its initial nature.

In Poland, investigations of changes in the relief of historic town centres were carried out on Cathedral Island in Poznań (Kaniecki, 2004, 2013; Zwoliński et al., 2017), in the Old Town in Toruń on an area of 7 km^2 (Molewski & Juśkiewicz, 2014; Molewski, 2015) and in the historic centre of Kraków on an area of 9 km^2. In Toruń, the initial relief of the study area was reconstructed and the boundaries of landforms prior to the 13th century were indicated. In both the Toruń and Poznań examples, spatial differentiation of the thickness of cultural deposits was determined which showed variation in the range 0-10m. In the historic centre of Kraków such investigations started as early as at the end of the 19th century and was intensified in the 1950s – 1970s. However, detailed reconstruction of the relief prior to the 13th century has not so far been carried out, despite rich sources of geological, geoengineering, archaeological and historical data as well as old maps and panoramic drawings of the town. The literature contains only fragmentary information concerning the former relief of Kraków city centre, and some information, unfortunately, is inconsistent. Despite good recognition of the contemporary relief of the Kraków area (Tyczyńska, 1968a,b; Tyczyńska & Chmielowiec, 1980) there is a gap in geomorphological knowledge as regards complex analysis of the initial relief of the historic town centre.

This work aims to fill this gap. The work represents the authors` vision of the relief of the study area before making changes in the planning structure of the town in the mid-13th century. The work is based on numerous published and unpublished information sources and supplemented with the results of the authors` research.

Location, geology and geomorphology of the study area

The narrowest section of the Vistula valley is located within the boundaries of Kraków, where the Polish Uplands border on the Western Carpathians, which results in a discontinuity in the Subcarpathian Basin (Fig. 1A). The Małopolska Upland, which represents the central part of the Polish Upland, is in Kraków built from Jurassic limestone and locally by Cretaceous marl (overlain by loess deposits). They form a number of tectonic horsts and grabens lowering towards the south (Gradziński, 1972; Rutkowski, 1989a,b, 1992, 1993). The external part of the Western Carpathians is built from flysch sediments. The bottom of the Vistula valley and its tributaries is covered by Pleistocene and Holocene alluvial deposits, locally peat deposits (Mamakowa, 1970; Bogacz et al., 2003, 2004). Within the most southern part of the Małopolska Upland called Kraków Gate (BK), three areas have been distinguished (Kondracki, 2000)

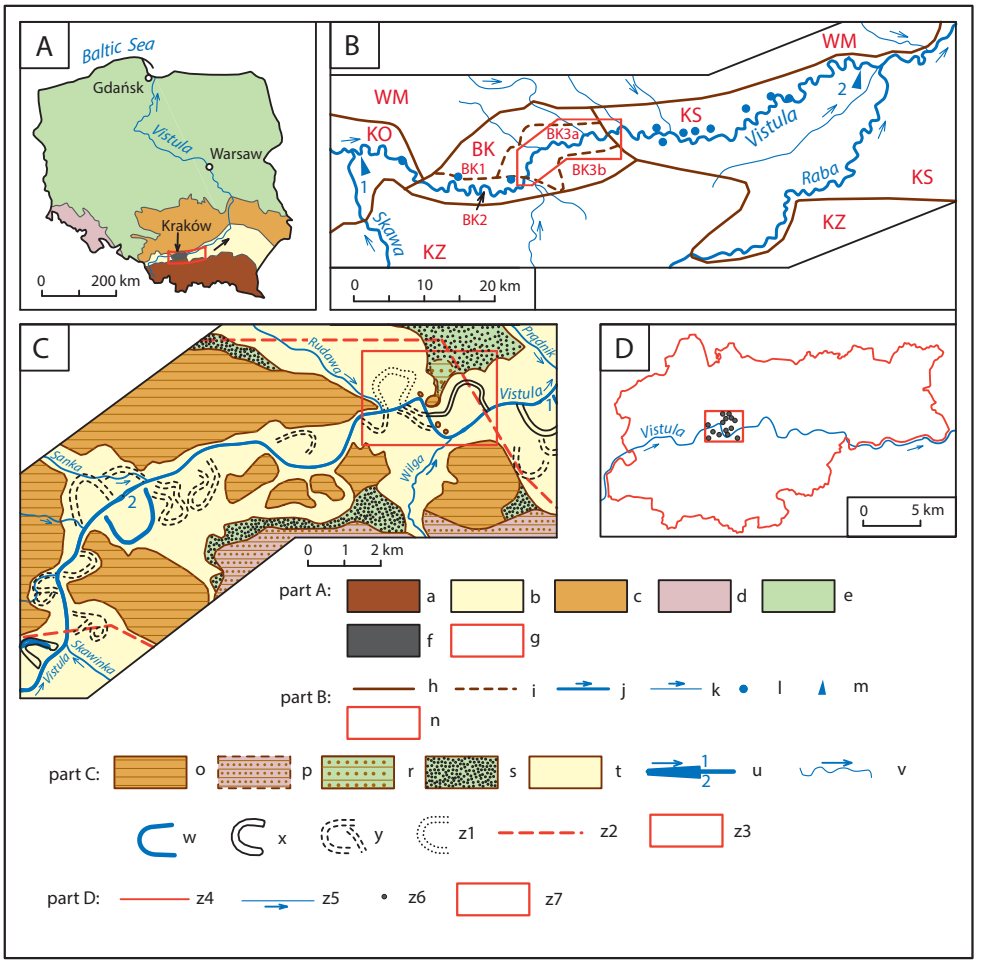

Figure 1. Location of the study area

A – within the boundaries of Poland in relation to the main geomorphological units; B- more detailed map of the borderland of the Polish Uplands, the Western Carpathians and the Sandomierz Basin; C – in the Kraków Landbridge; D – in relation to the boundaries of Kraków. Part A: a – Carpathians; b – Subcarpathian Basins; c – Polish Uplands; d – Sudetes; e – Polish Lowlands; f – Kraków Gate; g – area shown in part B. Part B: h – limit of geomorphological units: KZ – Western Carpathians, KO – Oświęcim Basin, KS – Sandomierz Basin (KO and KS – parts of Subcarpathian Basins), WM –Małopolska Upland (part of Polish Upland); i – limit of selected geomorphological sub-units: BK – Kraków Gate: BK1 – Cholerzyńskie Depression, BK2 – Spytkowice-Skawina Graben, BK3 – Kraków Landbridge: a – exposed limestone hills, b – limestone hills covered by Miocene deposits; j – main rivers; k – other rivers; l – location of the palaeomeanders investigated; m – gauging stations on the Vistula river taken into account in the study (1 – Smolice, 2 – Sierosławice); n – area shown in part C. Part C: o – exposed limestone hills; p – limestone hills covered by Miocene sediments; r – r - limestone hills covered by a thin layer of Quaternary and Holocene sediments; s – Quaternary terraces; t – Holocene terraces; u – Vistula river, weirs: 1 – Dąbie, 2 – Tyniec; v – other rivers; w – oxbow lakes; x – abandoned channels (since ca. 1850); y – traces of abandoned channels; z1 – palaeomeander discussed (study area); z2 – limit of Kraków Landbridge; z3 – area shown in part D and in Figs. 5, 7 –10. Part D: z4 – limit of Kraków City; z5 – Vistula river; z6 – areas settled up to the 12th century (within the study area only); z7 – centre of the city (study area).

(Fig. 1B), and among these, the eastern part of the Kraków Landbridge with its limestone hills (BK3a) has been studied in detail. Part of the Sandomierz Basin (KS) neighbouring to the east and belonging to the Subcarpathian Basin was also included in the investigation. In the area of the Kraków Landbridge, lying between limestone hills of tectonic origin (horsts), the Vistula river flows along one of the tectonic grabens. Narrow water gaps (0.3 km) bordered by over 20 m high rocky walls occur in this area (Fig. 1C). Pleistocene terraces occur locally in the valley bottom. Their embankments, with an arching course, resulted from migration of the river (Setmajer, 1973; Tyczyńska & Chmielowiec, 1980). The rest of the valley bottom is represented by the Holocene floodplain with palaeomeanders of various ages. Isolated limestone hills, with a height from several to over 40 m, rise above this surface. The Vistula river on the Kraków Landbridge (and along its whole course in the Subcarpathian Basins) shows a meandering course, which has been changed as a result of river regulation works.

The study area is located in the centre of Kraków. Its area is 9 km^2. It includes the eastern part of the Kraków Landbridge and a small adjacent part of the Sandomierz Basin (Fig. 1C), and it represents 3% of the area of Kraków (Fig. 1D). The study area consists of 4 isolated limestone hills (Fig. 1C), which rise above the floodplain, including the highest, Wawel Hill, located in the centre, and a number of limestone horsts overlain by a thin layer of Pleistocene and Holocene sediments. Horsts covered exclusively by cultural deposits occur within the Old Town and its neighbourhood (Kmietowicz-Drathowa, 1971; Gradziński, 1972; Radwański, 1975; Rutkowski, 1989a,b, 1992, 1993). The study area also includes fragments of higher limestone hills: the eastern part of Saint Bronisława Hill – near Salwator, northern part of Skałki Twardowskiego Hills and northern part of Krzemionki Hills. The study area also includes a part of the Pleistocene terrace covered by the large alluvial fan of the Prądnik river, where the Old Town is located. Most of the central area of Kraków is located on the Holocene floodplain with traces of old channels and two paleomeanders of the Vistula river (Kmietowicz-Drathowa, 1965; Tyczyńska, 1968a,b; Radwański, 1972, 1975; Tobiasz, 1977; Humnicki, 1979; Rutkowski, 1989a,b). Two tributaries of the Vistula river (the Rudawa and the Wilga) (Fig. 1C) join the main river in the study area and the mouth of next tributary (the Prądnik) is located on the eastern side of the area.

Selection of the study area and time range of the studies

While selecting the area to be investigated, the distribution of centres of settlement which had existed before the 13th century in the area of present-day Kraków was taken into consideration (Radwański, 1975). At that time, settlement density in this area was the highest in the study area (Fig. 1D): until the mid-13th century the Wawel Hill and the area to the north, as well as fragments of the limestone hills noted above and some areas within the floodplain, represented the so-called pre-establishment Kraków. Despite increasing population density before the reorganisation of the structure of the town in 1257 on the basis of the Magdeburg law (Radwański, 1975), changes in land relief should be regarded as insignificant compared to the changes which occurred together with the rapid development of Kraków from the mid-13th century onwards. The 1250s represent the end of the period, when human activity had no significant influence on the relief of the historic centre of Kraków. Therefore, the relief reconstructed in this work is related to the period before 1257. Later, together with changes in the spatial structure of Kraków (*Cracovia*), and after establishing the neighbouring towns (Kazimierz – *Casimiria* in 1355 and Kleparz – *Clepardia* in 1366) which were incorporated into Kraków over the following centuries, as well as the development of Kraków`s suburbs (i.e. Stradom – *Stradomia*), many changes

occurred in the topography of this area. This is indicated by an average 5 m thick layer of cultural deposits within the area of the Old Town with a maximum 14 m thick layer on the Wawel Hill (Tyczyńska, 1968b; Kmietowicz-Drathowa, 1974; Radwański, 1975; Bogacz et al., 2003, 2004; Grabowski, 2008; Sokołowski, 2009).

Views on the morphology of the study area before the changes in urban planning in the mid-13th century

Remarks on the morphology of the land in the area of historic centre of Kraków prior to the mid-13th century started to appear from the end of the 19th century. This information was based on archaeological investigations, geoengineering studies, historical records. Most of them come from the period 1945-2010, and the number of papers concerning that problem exceeded 200. The papers concerning the reconstruction of the morphology of the study area before the 13th century are mainly works of a contributory character, without important modifications due to the opinion of other authors. Most of these, especially the older ones, are based on poor documentation, which resulted in inconsistencies in opinion between their authors. Another reason for these divergent views at the beginning of the 20th century was the lack of a uniform method of interpretation of cultural deposits at the level of the primary soil, i.e. on the original undisturbed surface (Radwański, 1972, 1975). This resulted in different opinions on the relief in the area of e.g. the Old Town (Radwański, 1975 with cited papers).

Most information in the literature on the morphology of the centre of Kraków concerns the area within the boundaries of the Old Town and Kazimierz Town. Since the publication by Łuszczkiewicz (1899) some authors, based on a few outcrops and historical sources, expressed the view that on a narrow erosion remnant of high terrace in the southern part of Old Town, the fossilised channels of two arms of the Vistula river have been preserved under cultural deposits. It was also stated, that in the rest of the area of the Old Town an analogous situation concerns the former channels of the Vistula tributaries, i.e. the Rudawa and the Prądnik, together with their arms. It was also stated that in the western part of the Old Town, two 8 m deep ravines occurred and in the north some depressions were present which then became covered up (Dobrzycki, 1953; Mitkowski, 1955, 1957, 1968; Pierzchała, 1960; Jamka, 1963, 1971; Setmajer, 1973). There were also some remarks concerning the removal of limestone rocks (exposures of horsts) in the Old Town, as one of the first churches in the Kraków Romanesque style were built on such bed-rock. Radwański (1972, 1975) rose critically to these opinions and, based on the altitude of the primary ground level (m a.s.l.) determined in numerous outcrops (Fig. 2), excluded the existence of the above-mentioned fossil concave landforms (palaeochannels, ravines, other depressions) within the Old Town. The review of opinions on the former relief of the historic centre of Kraków was prepared by Kmietowicz-Drathowa (1971, 1972, 1974), and her views coincided with Radwański (1975) and the other results from investigations on the relief in the centre of Kraków completed at that time (Tyczyńska, 1968a,b). Similar opinions were presented by Grabowski (2008) and Sokołowski (2009).

Even greater differences in opinion are found regarding the former course of the Vistula and its tributaries within the central area of Kraków (Łuszczkiewicz, 1899; Bąkowski, 1902, 1935; Dobrzycki, 1953; Mitkowski, 1955, 1957; Pierzchała, 1960; Żaki, 1962; Kmietowicz-Drathowa, 1965). Tobiasz (1977) and Humnicki (1979) investigated this problem in detail but their opinions on some issues seem to be questionable. Usually, the discordant opinions concern the occurrence and limits of the Vistula meander upstream of Wawel Hill (Fig. 3). According to some authors (Radwański, 1975) this meander was intentionally cut off from the river by the inhabitants very shortly after 1257. As much

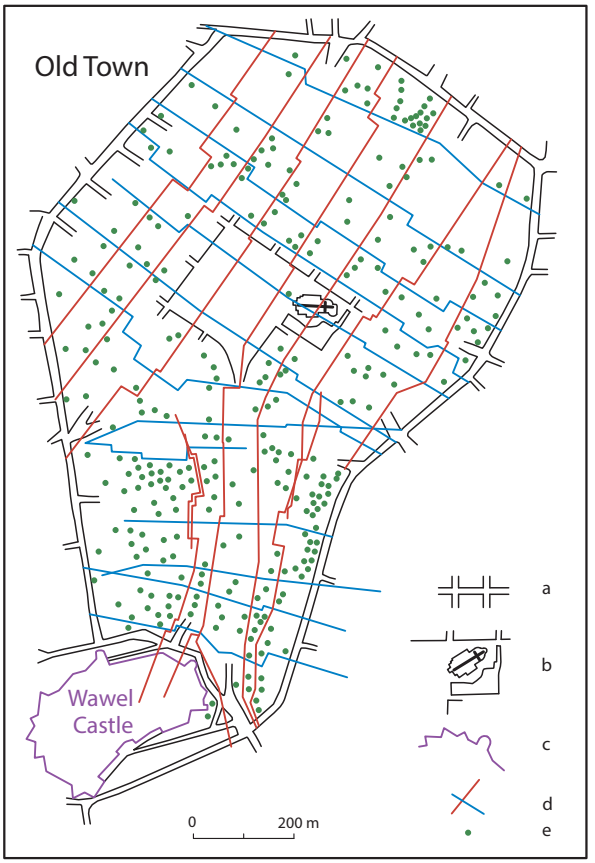

Figure 2. Distribution of archaeological sites within the Kraków Old Town, where the altitude (m a.s.l.) of the primary soil underlying the cultural deposits was determined, according to Radwański (1975)
a – old town ring road with crossroads marked; b – boundary of the Main Marketplace with street exits indicated, location of Blessed Virgin Mary Church; c – fortifications of the King's Castle on Wawel Hill; sites where archaeological investigations were carried out: d – profile lines; e – point sites.

time has passed, it is not now legible in land morphology, however some historical facts (Kmietowicz-Drathowa, 1965; Humnicki, 1979; Niezabitowski, 2007) indicate where it formerly occurred. Moreover, this area is at present excluded from multi-floor development. There were also differing opinions on how the two channels of the Vistula river downstream of Wawel Hill functioned (Fig. 3). The second branch, called the Old Vistula, functioned as a long meander and was filled with anthropogenic deposits in the 1870s. The adjacent areas were then used for urban settlement.

Materials and methods of investigation

Thematic literature concerning the study area was taken into consideration, especially papers on the original topography of the central area of Kraków, as well as contemporary and historical cartographic materials (selected maps of Kraków, e.g. Atlas Historyczny Polski, 2008) and maps from the website http://dawnemapykrakowa.pl. These materials were collected from the Institute of History of the Jagiellonian University, Institute of History

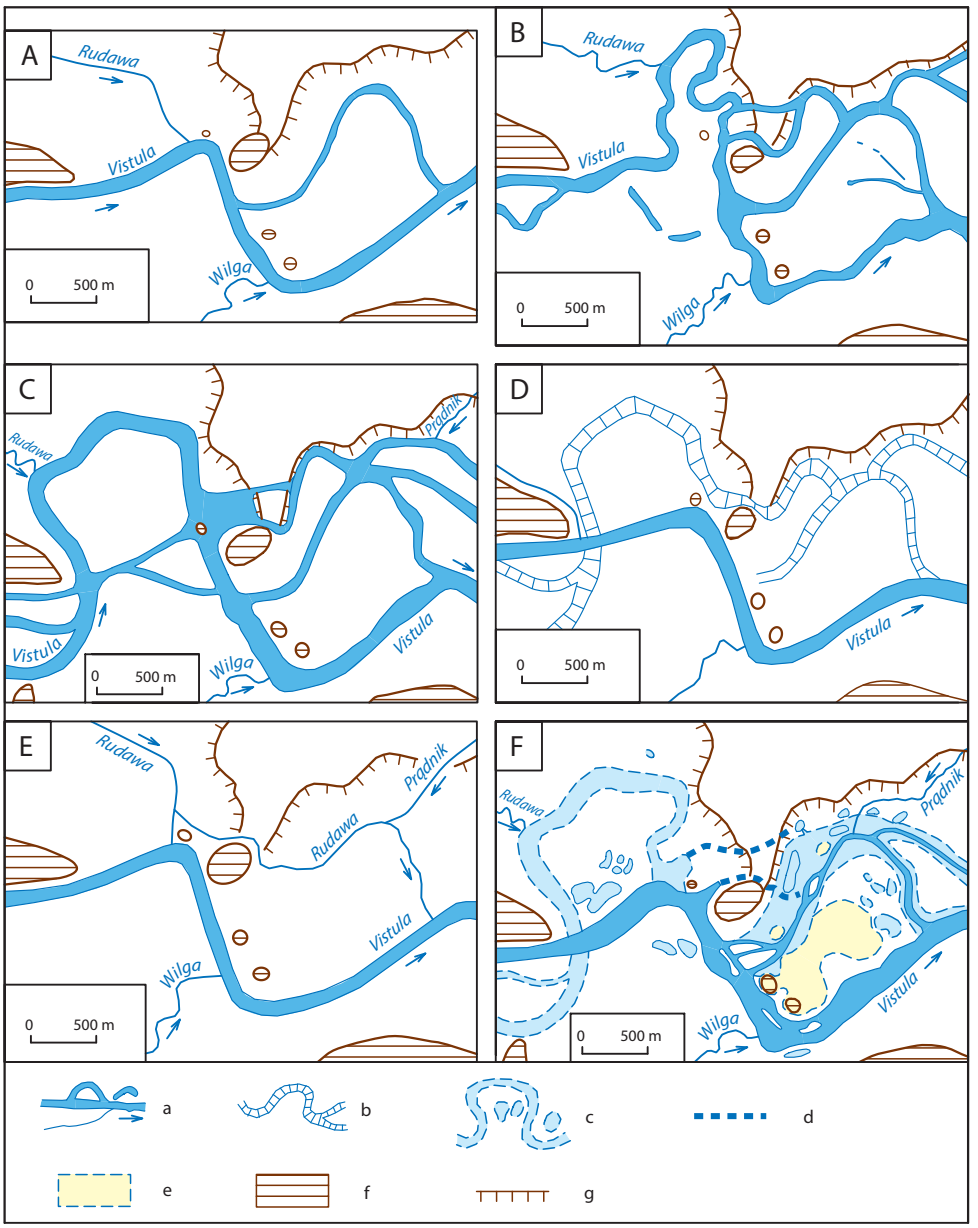

Figure 3. Course of the Vistula river in the study area until the mid-13th century according to: A – Żaki (1962), B – Mitkowski (1955), C – Mitkowski (1957), D – Pierzchała (1960), E – Dobrzycki (1963), F – Humnicki (1979)

A – Vistula river: a – main and secondary channels, tributaries, oxbow lakes; b – former channels of the Vistula river (according to D); c – former channels of the Vistula river (according to F); d – moats; e – non-flooded areas within the floodplain; f – limestone hills; g – escarpment of Pleistocene terrace.

of the Pedagogical University, Archaeological Museum, Archaeological Library of the Jagiellonian University and Provincial Office of Protection the Antiquities in Kraków. Selected sheets of the geomorphological map (1:25,000), geological map (1:50,000) and hydrographical map (1:25,000) of Poland were also used.

Maps found in archaeological papers (Żaki, 1962; Jamka, 1963; Kmietowicz-Drathowa, 1974; Radwański, 1975; Humnicki, 1979) formed the basis for the reconstruction of the relief in the period before the mid-13th century. In these maps, the altitudinal range of the primary ground surface is shown with contour-lines (m a.s.l.) based on a dense network of control points. Setmajer's map (1973) based on geoengineering investigations, shows the elevation of the primary ground surface (= the basal-surface of the anthropogenic deposits) giving its precise value at many points, mainly in the area of the Vistula floodplain in palaeochannels and on sand bars. This map shows the boundaries between these landforms. Special attention should be paid to Radwański's map (1975), on which the primary topography in the area of the Old Town has been determined based on the densest network of control points (Fig. 2). In some places on this map, there are more than 20 control points per ha. Others maps mentioned above include the whole of the study area in the centre of Kraków and even areas beyond its boundaries. Radwański (1975) shows that it is only possible to make a reliable contour-line map showing the altitude of the primary ground surface (m a.s.l.) if one bases one`s study on a dense network of control points, i.e. if the distance between them is smaller than 20 m [authors` remarks]. In this manner we can eliminate possible errors in the course of a contour-line caused by numerous (especially in the Old Town or Kazimierz Town) former deep drain pits totally filled up with cultural deposits, or by disturbances at the contact with primary ground level – cultural deposits along former roads and on marketplaces.

Reconstruction of the course of the Vistula, and its branches and tributaries before the mid-13th century in the area of the contemporary centre of Kraków is based on the maps studied (Dobrzycki, 1953; Mitkowski, 1955, 1957; Pierzchała, 1960; Żaki, 1962; Humnicki, 1979) (Fig. 3), in compliance with the comments made by Kmietowicz-Drathowa (1965, 1974), Tobiasz (1977) and Niezabitowski (2007), and also some facts from the history of medieval Kraków (Radwański, 1975) and information included in former pictures of the town (Atlas Historyczny Polski, 2008). Based on these materials, depressions were found on the Vistula floodplain, which represented wetlands with peat deposits surviving for many centuries after 1257 and some were occupied by ponds. Based on papers (Kmietowicz-Drathowa, 1971; Gradziński, 1972; Setmajer, 1973; Radwański, 1975; Kleczkowski & Myszka, 1989) such exposures of limestone rocks were found within the Old Town and on the Vistula floodplain which used to be formed of limestone hills and have now been lowered or built up.

The opinions concerning the geometry of the Vistula meander upstream of Wawel Hill which was cut off from the river after 1257 (Radwański, 1975), i.e. its mean curvature radius (*r*) and mean channel width (*w*), are inconsistent (Fig. 3B-D,F). In order to estimate the reliable horizontal dimensions of this river meander (*r, w*) and mean channel depth (*d*), it was decided to carry out comparative investigations in 11 Vistula oxbow lakes filled with deposits and which are located upstream and downstream of Kraków in the river section between the Skawa confluence and the Raba confluence (Fig. 1B). The selected oxbow lakes represent the Vistula meanders which were cut off no earlier than the turn of the 18th and 19th century and no later than the mid-19th century, which is indicated by analysis of the following maps: Mieg (1779-1782), Gross (1809-1815), Liesganig (1824), Kummerer Ritter von Kummersberg (1855), General-Karte .... (1868), Die Spezialkarte .... (1890-1916). These oxbow lakes contain the preserved geometry of the

pre-regulation channel of the Vistula river (Łajczak, 1995) and therefore they may represent an analogy of the former river meander upstream of Wawel Hill, whose parameters are otherwise impossible to determine. The analogical oxbow lake may also be compared with another former Vistula meander in the centre of Kraków downstream of Wawel Hill, the radius (*r*) of whose curvature can only reliably be determined on the basis of historical maps.

The oxbow lakes selected for comparative analysis represent the section of the Vistula, where mean discharge between the gauging stations – in extreme locations (Fig. 1B) increases from 93 to 114 $m^3 \cdot s^{-1}$, which is by 23%. In such a situation, the functioning of the selected oxbow lakes may be assumed, according to Gregory (1987), to be comparable in terms of hydrological conditions. Therefore, all the 11 selected oxbow lakes fulfil the criteria of meanders analogous to the two former Vistula meanders located upstream and downstream of Wawel Hill. The method of determining the parameters (*r, w, d*) of each analogous meander as a mean value of 5 profile lines is shown in Fig. 4. Mean values of these parameters from 11 analogous meanders represent the basis for evaluating the dimensions of the two Vistula meanders studied in the centre of Kraków. The measurements of the 11 analogous meanders carried out by the authors from May to November 2018 included e.g. boreholes with the use of a geological drill.

Contour lines were drawn (m a.s.l., every 1 m) on the basis of the maps included in the papers (Żaki, 1962; Jamka, 1963; Kmietowicz-Drathowa, 1974; Humnicki, 1979), and which cover the study area in the centre of Kraków. These show the morphology of the primary ground level, i.e. the topography of the study area before the deposition of cultural deposits which started in the mid-13th century. In the area of the Old Town, the most precise option considered from the variants of the contour lines – was the one selected according to Radwański (1975). The course of the

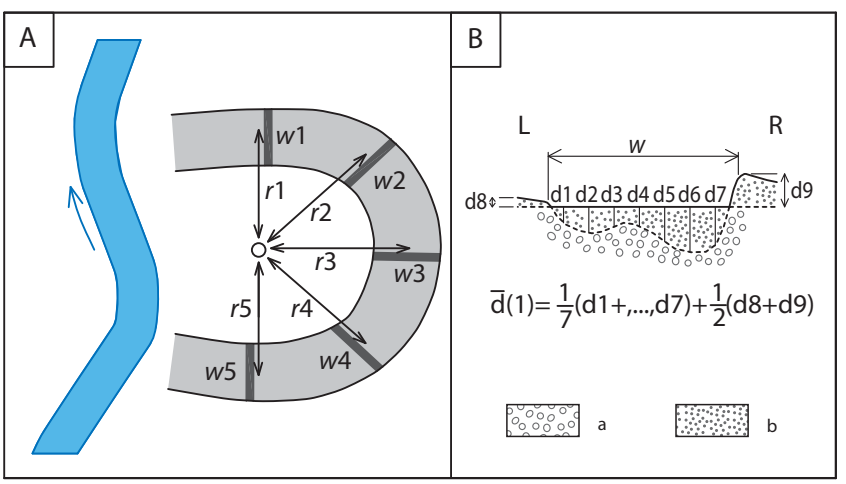

Figure 4. Diagram explaining how the geometrical parameters of the deposit-filled palaeomeanders were estimated

A – the estimation of the palaeomeander radius (*r*) and channel width (*w*) along 5 profile lines in relation to the contemporary course of the river channel; B – estimation of mean channel depth (*d*) in the cross-section of the palaeochannel including depths d1, ..., d7 within the channel filled with deposits and d8, d9 which represent the height of the concave and convex banks above the top of the sediments which fill the palaeochannel. Banks of the palaeochannel: L – left, R – right, a – channel deposits, b – flood deposits.

contour lines of the primary ground level (m a.s.l.) in the area of the Vistula floodplain was drawn with maximum accuracy based on Setmajer's maps (1973) which made it possible to show the general features of the sandy bars, decantation depressions, overflow channels and limestone hills. Based on the maps mentioned above, contour-lines were drawn (every 1 m a.s.l.) showing the topography of the primary ground level. Manual digitalisation of the contour-lines and altitude points was carried out, which were interpolated with the use of geostatistical tools.

The probable course of the Vistula channel from the period between the 10th and 13th centuries became integrated in the picture of the topography of the study area (Fig. 5). Opinions concerning the occurrence of the Vistula meander upstream of Wawel Hill based on historical premises (Mitkowski, 1955, 1957; Kmietowicz-Dratkowa, 1965; Humnicki, 1979; Niezabitowski, 2007), and the opinions of the authors cited together with some others (Żaki, 1962; Jamka, 1963; Mitkowski, 1968; Kmietowicz-Drathowa, 1974; Radwański, 1975; Tobiasz, 1977), concerning the former occurrence of the two arms of the Vistula river downstream of Wawel Hill (where the northern arm formed as a meander) were all taken into consideration. The horizontal limit of the first meander was modified in relation to these authors taking into account some historical facts and local environmental conditions. In the two reconstructed meanders of the Vistula river, parameter (*r*) was adopted as the one in the analogous river meanders, whereas in the whole course of the Vistula channel, parameters (*w*) and (*d*) were adopted. The reconstruction of the hypsography of the study area in the 13th century thus obtained (Fig. 5), makes it possible to evaluate local height differences before Kraków was founded in the 13th century and Kazimierz was founded in the 14th century.

In order to generate a digital elevation model (DEM) showing the topography of the study area before the mid-13th century, all contour lines and Vistula channel were digitized, which are shown in Figure 5A. Structural analysis was carried out together with a cross-validation test (Zarychta A. & Zarychta R., 2013; Zarychta R. & Zarychta A., 2013). The ordinary kriging method (OK) was used, which belongs to the group of geostatistical methods. OK is recognized as a BLUE – *Best Linear Unbiased Estimator*, which minimizes the error variance and gives the best results (Clark, 1987). OK provides a correct and accurate modelling of the spatial variability, which is not possible when using deterministic methods. The final cartographic work (Fig. 5B,C) was prepared with the use of QGIS and Surfer software.

Based on the probable hypsography of the study area, which was recognised, and taking into account information from the literature (Tyczyńska, 1968a,b; Setmajer, 1973; Radwański, 1975), selected elements of the palaeogeography of this area were indicated (Fig.7) and the mid-13th century relief was reconstructed (Fig. 8) based in some situations on regularities observed in the present-day Vistula river in the Carpathian foreland (Łajczak, 1995). Next, taking into account additional information from the literature (Atlas Historyczny Polski, 2008) on the former limits of flood water, wetlands and ponds were determined (Fig. 9). Finally, considering the geomorphological features of the study area, the authors evaluated the availability of this area for the development of settlement in the period before Kraków was established (mid-13th century) (Fig. 10).

Results

Hypsography

The hypsography of the study area in relation to the mid-13th century is shown by the application of the dense contour lines method (Fig. 5) which makes it possible to determine boundaries between five groups of landform which differ in altitude.

This area includes fragments of three vast limestone hills (Fig. 1C; Fig. 5): eastern part of Saint Bronisława Hill (SBH), northern part of Skałki Twardowskiego Hills (STH) and Krzemionki Hills (KH). The highest point of the last

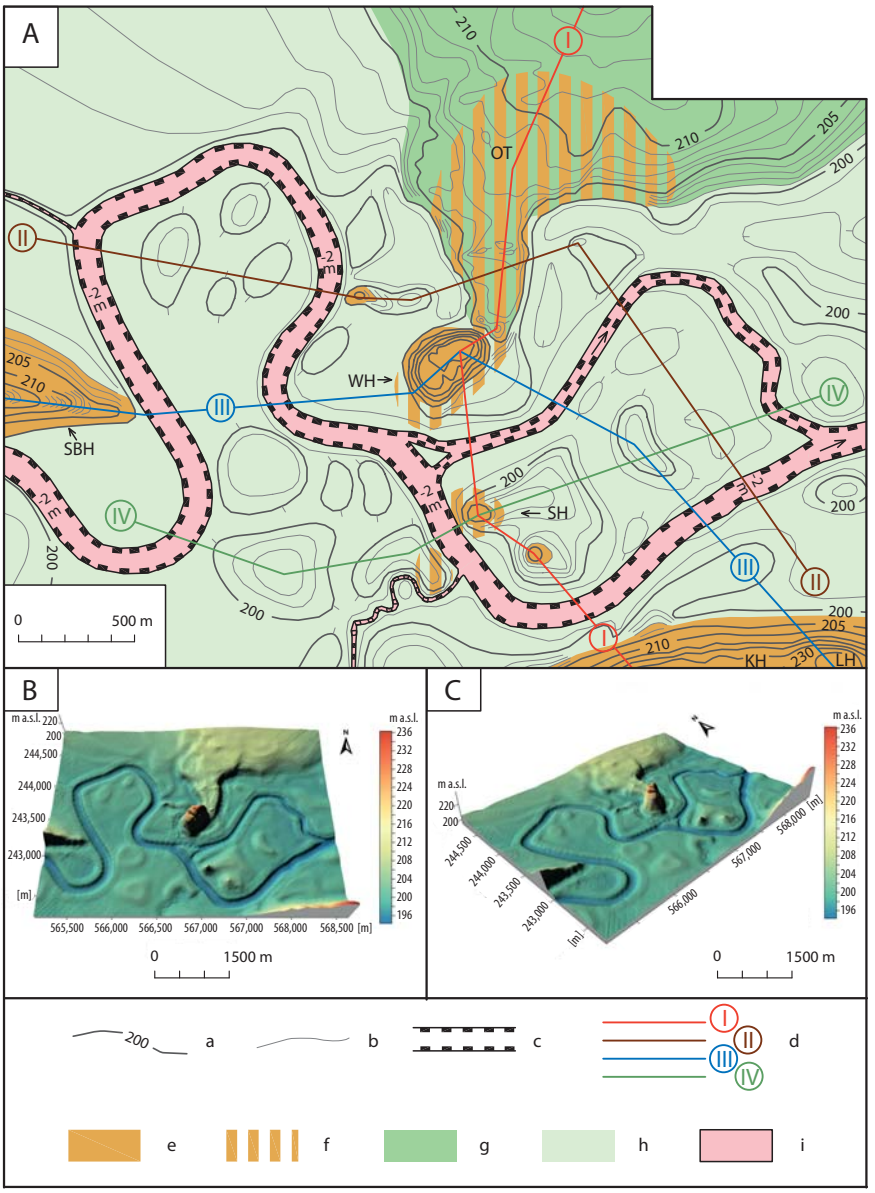

Figure 5. Reconstruction of the hypsography of the study area before the 13th century (according to the authors)

A – contour line map (methods of completion explained in the text); digital model showing the topography of the study area: B – DEM in the vertical projection based on A; C – DEM in the diagonal projection based on A (N direction is marked). In part B and C an altitudinal scale (m a.s.l.) is given. a – contour lines every 5 m; b – contour lines every 1 m (in the areas of limited land slope); c – river channels (in the case of the Vistula, mean channel depth is given – the method is explained in the text); d – course of profile lines No I, II, III and IV. Areas located at different altitudes: e – limestone hills, f – fragments of tectonic horsts covered by a thin layer of Pleistocene, Holocene and/or cultural deposits; g – Pleistocene terrace; h – floodplain; i – river channels. WH – Wawel Hill, SBH – Saint Bronisława Hill, KH – Krzemionki Hills, LH – Lasota Hill, SH – Skałka Hill, OT – Old Town.

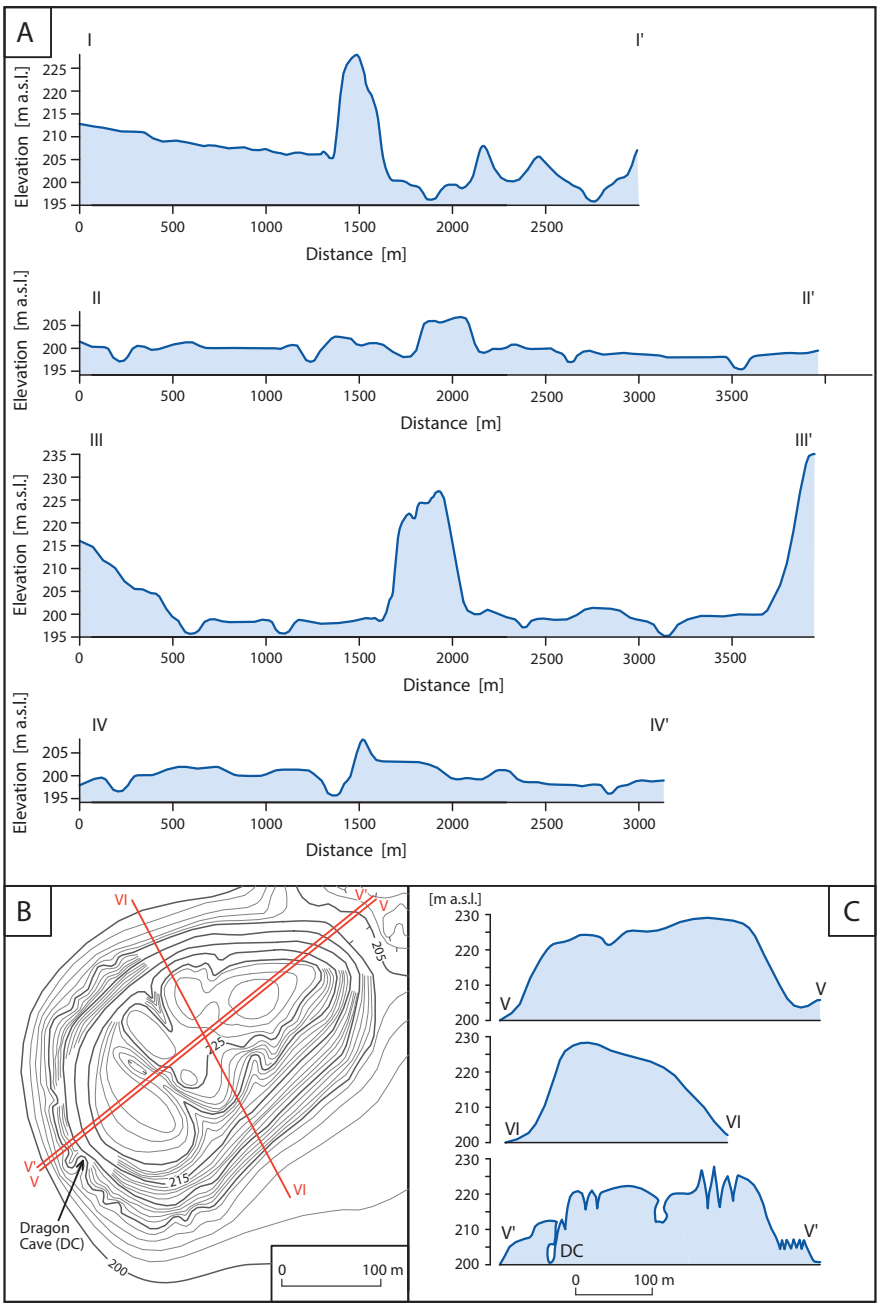

Figure 6. Reconstructed morphological profiles across the study area (situation before the mid-13th century)

A – morphological profiles No I, II, III and IV (location in Fig. 5); B – contour-line map of Wawel Hill and location of morphological profiles No V and VI (contour lines every 1 m); C – morphological profiles across Wawel Hill. Profiles No I-VI prepared by the authors. In part C, profile No V' according to Kleczkowski & Myszka (1989) is marked, this location is similar to Profile No V.

hills (Lasota Hill – LH) exceeds 235 m a.s.l. There are also 4 isolated limestone hills, among which the highest centrally located one – Wawel Hill (WH) reaches 228 m a.s.l. (Fig. 5). The height differences within the limestone hills usually exceeded 10 m in the past, and in the case of Wawel Hill as much as 30 m, and Lasota Hill 37 m. In some places, limestone horsts occur in the largest area within the Old Town (OT), which in the mid-13th century were covered by a thin layer of Pleistocene and Holocene deposits, however some were exposed (Kleczkowski & Myszka, 1989).

The Pleistocene terrace includes the NE part of the study area, and in its southern part is formed as narrow spur (on the substratum of shallow limestone horsts) – joined to Wawel Hill. The altitude of the terrace increases towards the N of the study area and in the 13th century varied between 205 and 214 m a.s.l. The escarpment of this terrace used to be 7-10 m high in the past and its southern part was the steepest. The Vistula floodplain, which dominated in the study area, had an altitude 197-204 m a.s.l. prior to the 13th century. At that time local height differences (above the Vistula channel) reached 3-4 m in the area of floodplain, however most of them did not exceed 2 m. The Vistula channel was about 70 m wide and about 2 m deep. Because the course of the river was meandering, the maximum channel depth was probably twice as large in the undercut parts of the meanders. Up to the 13th century, the Vistula split into two arms to the south of Wawel Hill and, according to Mitkowski (1955), the northern channel was narrower and shallower than the southern channel (the former one dried up periodically). Height differences in the area of floodplain together with the Vistula channel might have locally reached 8 m, and in the whole area studied could have even exceeded 40 m.

The variation of local relative height within the study area, including different landforms, is shown in profiles I-IV (Fig. 6). Attention should be paid to the asymmetry of limestone hills: the N and W slopes are steeper than the S and E slopes. Asymmetry of slope inclination is especially visible in the case of Wawel Hill (Fig. 6B,C).

Selected elements of palaeogeography

After partial exposure of the limestone hills lying under a cover of Miocene clay in the Kraków Landbridge, further development of the relief of the study area depended on the deepening of the Vistula valley and its tributaries, and later on the forming of vast fluvioglacial fans. This predominantly occurred by the northern tributaries (the Rudawa, the Prądnik) during the South-Polish glaciation, which then became eroded (Tyczyńska, 1968a,b). During the Mazovian (Holsteinian) interglacial the Vistula flowed north of the Saint Bronisława Hill (SBH), forming the wide Rudawa Valley (RV), which developed in a tectonic graben (Fig. 1C; Fig. 7). Until that time the limestone hills were undercut by river water on the N and NW side. During the stadial of the Odra glacial maximum the Vistula turned south to the neighbouring tectonic graben within the Kraków Landbridge (Feliksiak, 1988) and the limestone hills started to be undercut by river water, predominantly on the W side.

Setmajer's investigations (1973) made it possible to reconstruct the directions of flow of the Vistula in the area of the contemporary centre of Kraków since the end of the last glaciation (Fig. 7). This made it possible to reconstruct the channel course until the late Holocene and also made it possible to correlate the age of erosional undercuts of the Pleistocene terrace with these facts. Arched undercuts of this terrace, which are of a larger radius of curvature and distant from the southern spurs of the terrace adjacent to Wawel Hill (WH), result from lateral erosion of large meanders of the Vistula river, which were functioning at the end of the last glaciation. The large-radius erosional undercuts which formed at that time were also recognised in other sections of the Vistula valley (Klimek, 1987; Kalicki & Starkel, 1989).

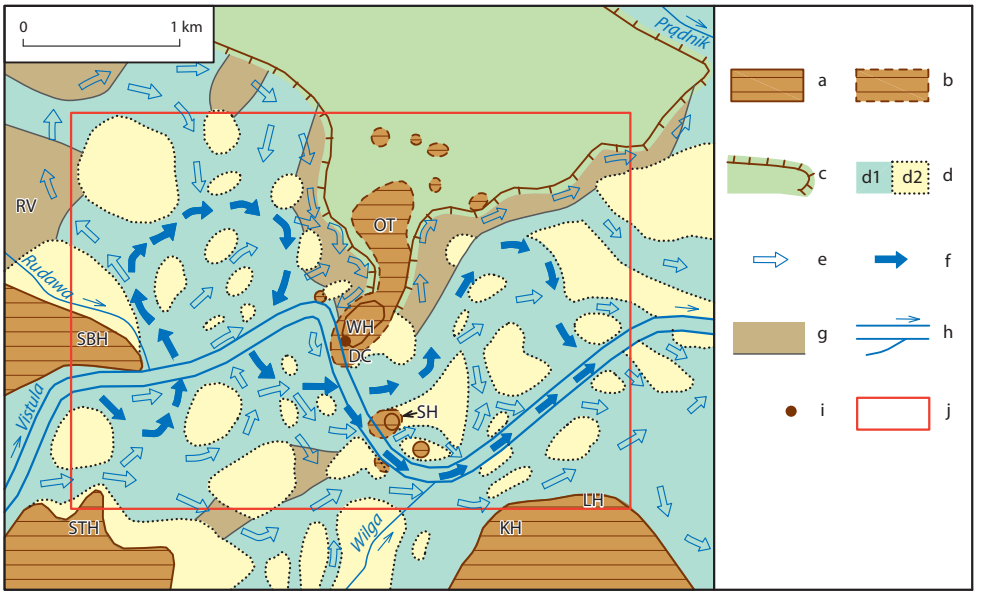

Figure 7. Selected elements of the palaeogeography of the study area

Reconstruction of the directions of flow of the Vistula at the end of the last glaciation and in the Holocene (last 12 thousand years) in the area of contemporary centre of Kraków, according to Setmajer (1973). The limits of sandy bars which, according to the author cited are traversed by river currents, are marked. The tip of the Pleistocene terrace reaching Wawel Hill (WH) to the north to the Old Town Horst, where outcrops of Jurassic limestones are locally overlain by Cretaceous marls, were exposed or covered by a thin layer of Quaternary deposits, according to Gradziński (1972) and Rutkowski (1989a,b, 1992, 1993). The limits of peat deposits from the Atlantic period of the Holocene according to Mitkowski (1957), Kmietowicz-Drathowa (1971), Radwański (1975), Tobiasz (1977). a – exposed limestone hills (WH- Wawel Hill, SBH – Saint Bronisława Hill, KH – Krzemionki Hills, LH – Lasota Hill, SH – Skałka Hill, STH – Skałki Twardowskiego Hills); b – fragments of some tectonic horsts including the Old Town Horst totally or partially covered by Quaternary deposits; c – Pleistocene terrace; d – Holocene valley bottom (d1 – former river channels, d2 – sandy bars); e – former directions of flow of the Vistula; f – former directions of flow of the Vistula taken into consideration in this work; g – peat deposit; h – contemporary course of the Vistula and its tributaries; i – Dragon Cave (DC); j – area shown in Figures 8-10. RV – Rudawa Valley.

The undercuts of the Pleistocene terrace near Wawel Hill are of Holocene age and resulted from development of smaller meanders of the Vistula river. They show a smaller radius of curvature and their escarpments are steeper (Fig. 5A; Fig. 7).

In the Holocene (Fig. 7), peatbogs developed in the inactive channels of the Vistula river at the foot of the escarpment of the Pleistocene terrace, or even directly at the northern foot of Wawel Hill (Mitkowski, 1957; Kmietowicz-Drathowa, 1971; Radwański, 1975; Tobiasz, 1977). Peat deposits are also present in the Rudawa Valley (RV), where deposits of bog iron developed (Mitkowski, 1955). They were also found on the southern side of the former course of the Vistula, near the Wilga confluence. No peat deposits were determined to have existed along the reconstructed course of the Vistula up until the mid-13th century (Fig. 5A; Fig. 7).

Morphology and hydrography

Despite the dominating limit of the floodplain, the relief of the centre of Kraków before the mid-13th century should be regarded as more varied than today because formerly

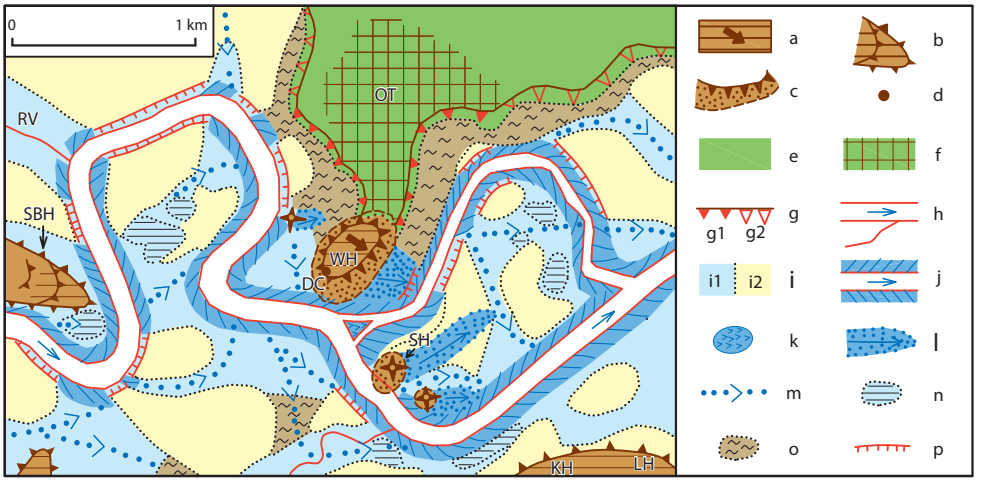

Figure 8. Distribution of landforms in the study area in the mid-13th century (proposed variant of geomorphological map, according to the authors)

a – limestone hills (the arrow pointing to Wawel Hill, WH, shows the direction of lowering of the plateau); b – slopes of limestone hills, denudation flattening (elongated zigzag in the symbol means a longer and less inclined slope); c – erosion platforms at the foot of limestone slopes covered by a thin layer of Holocene deposits; d – Dragon Cave (DC); e – Pleistocene terrace built up over the alluvial fan of the River Prądnik; f – fragment of a Pleistocene terrace where tectonic horsts (outcrops of Jurassic limestones and Cretaceous marls in the area of the Old Town Horst) occur under anthropogenic deposits (under "cultural layer"); g – escarpment of Pleistocene terrace (g1 – steep, g2 – gently inclined); h – channels of the Vistula, its arms and tributaries; i – floodplain (i1 – frequently flooded, i2 – flooded during catastrophic floods); j – levees; k – sandy bars plugging the entrance to a secondary channel of the Vistula; l – sandy shadows formed on the eastern side of the limestone hills (downstream of former flow direction of the Vistula); m – overbank channels; n – stagnation planes with accumulation of mineral material; o – planes of biogenic accumulation (peatbogs); p – probably escarpments of sandy bars. For other explanations see Figure 7.

different categories of landform were more distinct in morphology and their boundaries were clearer. Later, together with the growth of the cultural layer, the surface rose and, simultaneously, the surface morphology became flattened.

Up until the 13th century, the limestone hills rose over 20 m above the Vistula river, which was flowing nearby, and in the case of Wawel Hill by about almost 30 m and with Lasota Hill (LH) by about 40 m (Fig. 8). These are asymmetrical hills with their plateaux inclined towards the Vistula. Their slopes show a large inclination, even exceeding 30° or more (e.g. Wawel Hill) and exposed towards the N and W. In the neighbourhood of the Vistula, these were rocky slopes, 10-20 m high. There was a clear contrast between the steep slopes of the hills and the flat surface of the surrounding area, especially to the N and W of Wawel Hill. Among the hills covered by the study, there are two plateaux on the eastern part of Saint Bronisława Hill (SBH), whereas other hills show only one plateau (Fig. 8). The primary morphology of the plateau was only studied on Wawel Hill (WH), where the occurrence of karst forms on the surface (karst karrens, sinks, gorges, rocky forms) was noted under the cover of cultural deposits (Jamka, 1961; Kleczkowski & Myszka, 1989). Height differences within the karst forms on original plateau of Wawel Hill locally reached 15 m (Kleczkowski & Myszka, 1989). Caves developed in this hill, like in the other hills investigated. The most famous one is the Dragon Cave (DC), over

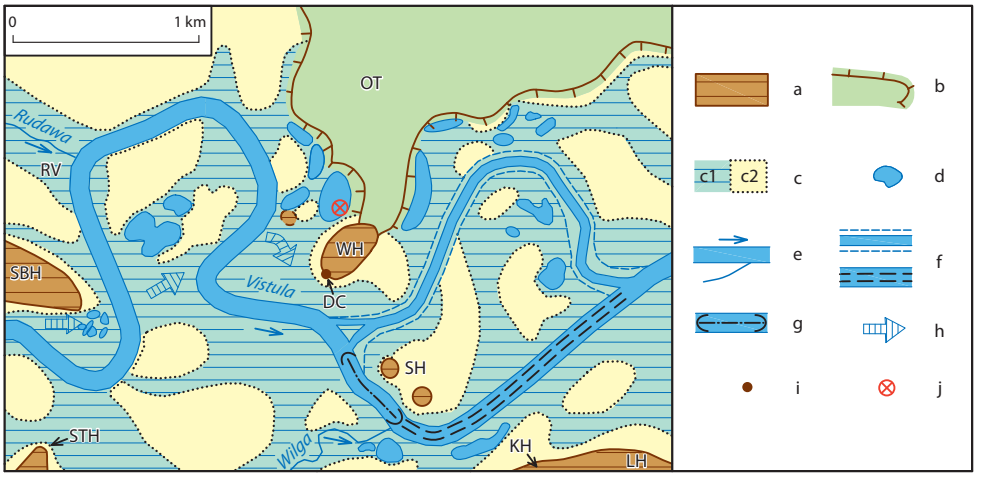

Figure 9. Probable limit of frequently flooded areas and wetlands on the Vistula floodplain in the study area in relation to the course of the Vistula until the mid-13th century. Partly based on Setmajer (1973) and Atlas Historyczny Polski (2008).

a – limestone hills; b – Pleistocene terrace; c – Holocene bottom of the Vistula valley (c1 – frequently flooded wetlands, c2 – rarely flooded areas, only during catastrophic floods); d – areas with stagnant water; e – the Vistula river, its branches and tributaries; f – Vistula branches, whose channels have become in turn narrower or wider; g – section of the Vistula channel which periodically became shallower or even disappeared; h – Vistula course on the western side of Wawel Hill (WH) which was in use since the 15th-16th century; i – Dragon Cave (DC); j – fragment of a floodplain with stagnant flood water (in the form of a "bay") where the accumulation of wood debris occurred. For other explanations see Figure 7.

10 m deep, which is located in the Wawel Hill massif itself (Fig. 6B; Figs. 7-10).

Fragments of tectonic horsts were recognised at the shallow depth under the anthropogenic and alluvial sediments (depth: 5-15 m) around Wawel Hill (WH) and Skałka Hill (SH) and also in other places (Fig. 5A; Figs. 7-8) (Kmietowicz-Drathowa, 1964; Setmajer, 1973; Kleczkowski & Myszka, 1989). This fact may be interpreted, according to Kmietowicz-Drathowa (1964), as a result of the erosional undercut of the limestone hill slopes by the waters of the Vistula during the Quaternary, which resulted in the development of cliffs and erosional platforms. This form may determine the original horizontal limit of the plateaux of the tectonic horsts, which, because of long-lasting undercutting by the river (at least from the beginning of the Quaternary), became reduced to their contemporary dimensions.

Until the mid-13th century, the surface of the Pleistocene terrace which covers the NE part of the study area had elevations towards the north from 205 m a.s.l. at the foot of Wawel Hill to 214 m a.s.l. at the northern side of the Old Town (Fig. 5). The profile of the terrace towards the W-E looks like a plateau fringed with distinctive escarpments, which up until the 13th century used to be up to 7 m high in the southern part and 10 m high in the northern part. Because of the varied age of the undercuts of this terrace by the Vistula meanders, the escarpment was steeper in the southern part with an average slope of 20° before the 13th century (Fig. 5A).

The southern limit of the Pleistocene terrace in the centre of Kraków is locally conditioned by shallowly occurring outcrops of limestone rocks within tectonic horsts. The southernmost part of this terrace is formed of 200-400 m wide spur joined to Wawel Hill (Fig. 5; Figs. 7-8). Tectonic horsts shallowly occurring under Quaternary (locally only cultural) deposits within the Old Town

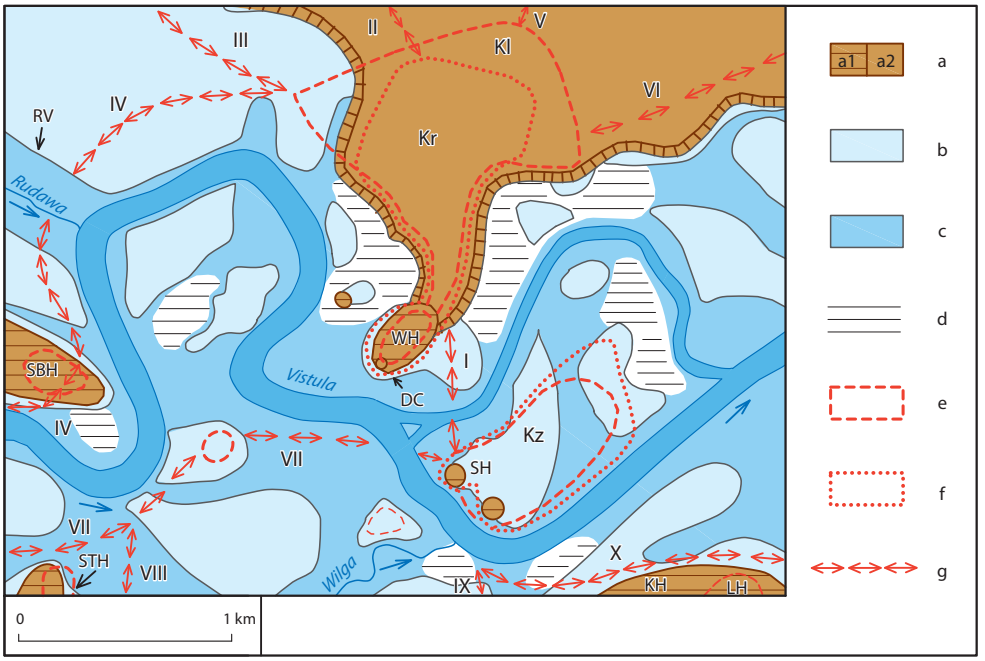

Figure 10. Usefulness of terrain for the development of settlement in the area of the contemporary centre of Kraków according to its state in the mid-13th century. Partly based on Humnicki (1979) and Atlas Historyczny Polski (2008)

a – areas located above the highest flood-stages (a1 – limestone hills, a2 – Pleistocene terrace); b – areas flooded during catastrophic floods; c – frequently flooded areas; d – places of flood water stagnation, e – limit of inhabited areas until the mid-13th century (the largest area including Wawel Hill (WH) and adjacent areas to the north representing an early town of Kraków (Kr) composed of settlements established under Slavic law); f – boundaries of towns established under the Magdeburg law: Kr – Kraków in 1257, Kz – Kazimierz in 1335, Kl – Kleparz in 1366, WH – fortified Wawel Hill with the King's Castle and the Cathedral; g – routes connecting Kraków with: I – Saint Stanisław Church on Skałka Hill, II – Poznań town, III – Wrocław town, IV – Moravia and Czechs, V – Mazovia, VI – Sandomierz and Kiev towns, VII – Benedictine Abbey in Tyniec, VIII – Cieszyn town, IX – southern frontiers of Poland in the Carpathians and with Hungary, X – Sącz town and Hungary. For other explanations see Figure 7.

and its neighbourhood counteract the threat of total erosion of this fragment of the terrace by the Vistula meanders to the W and E. This especially concerns those elements of the spur that is the southernmost, narrowest and bordered by high escarpments to the W and E (Fig. 8). Due to the occurrence of outcrops of limestone rock (Old Town Horst) in this fragment of Pleistocene terrace, the narrow spur represented a bridge rising above the wetlands and joining Wawel Hill with the area to the north (Rutkowski, 1989b).

In the relief of the part of the Pleistocene terrace mentioned, palaeochannels of the Vistula tributaries (the Rudawa, the Prądnik and their arms) were visible until early medieval times, as well as rock forms in places where the limestone horsts are found at the shallowest depth. These forms then became obliterated as settlement developed.

According to literature sources, on the Pleistocene terrace in the centre of Kraków, palaeochannels of the Prądnik and the Rudawa tributaries of the Vistula occur under cultural deposits, and there are different suggestions given by different authors to explain their courses (Bąkowski, 1902, 1935; Jamka, 1963, 1971; Setmajer, 1973; Radwański, 1975;

Tobiasz 1977). The network of these palaeochannels on the alluvial fans of the Rudawa and the Prądnik rivers which overlie the Pleistocene terrace of the Vistula could have developed before the deepening of the Vistula valley at the end of last glaciation during the process of permafrost melting (Rutkowski 1989a,b). As Jamka (1963) has pointed out, 8 m deep erosional cuts in the edge of the Pleistocene terrace overlain by cultural deposits in the western part of the Old Town, may be connected with the functioning of these palaeochannels. However, investigations by Radwański (1975) based on the analysis of the altitude of the primary soil roof in a dense network of measurement sites, rejected the occurrence of such cuts. This author also rejected the occurrence of the Rudawa palaeochannel within the Old Town, which according to some opinions should run along the Main Marketplace. Fossil elements of fluvial relief on the area of the Pleistocene terrace in the centre of Kraków have smaller height differences than were shown in the literature. These should be recognised as landforms which were visible in the relief of this part of the study area until cultural sediments became deposited on a larger scale, in particular from the mid-13th century onwards, thus disguising the former relief.

Another probable element of the relief of the southern spur of the Pleistocene terrace in the centre of Kraków until early medieval times was the presence of limestone rocks. The locations of the former occurrence of these rocks are shown in published geological profiles (Kleczkowski & Myszka, 1989). Rock forms were destroyed as the first Romanesque style churches were built on them in the 10th-12th centuries, i.e. before the establishment of Kraków in 1257. Traces of these forms were then obliterated by the growth of cultural deposits in succeeding centuries (Radwański, 1975).

The reconstructed hypsography (Fig. 5) and the recognised geology of the Holocene deposits (Kmietowicz-Drathowa, 1965, 1971, 1972, 1974; Tyczyńska, 1968a,b; Mamakowa, 1970; Setmajer, 1973; Tobiasz, 1977; Rutkowski, 1989a,b, 1992, 1993) make it possible to estimate the relief of the Vistula floodplain in the study area before the 13th century (Fig. 8). The largest areas represented frequently inundated fragments of the floodplain and those built up during floods, and also fragments of the floodplain only built up during catastrophic floods. The former are flat areas with height differences not exceeding 2 m, whereas higher located areas (height differences up to 4 m) form vast sandy bars, which have developed in the conditions experienced during the largest floods. The latter are marked on Setmajer's map (1973). Analogously to the current situation, levees were formed along the banks of the channel of the Vistula (Łajczak, 1995). Taking into account the smaller size of transport of clastic material, and in particular the suspended material, especially, in the Vistula of about 1000 years ago (due to a larger extent of forests in the river catchment) (Łajczak, 1999) as compared to the present situation, the vertical and horizontal dimensions of the levees were smaller than contemporary forms. To the east of four limestone hills rising above the Vistula floodplain, i.e. downstream of the former flow direction of the Vistula (taking into account the dominant direction of the river flow), sandy bars up to 500 m long were formed (Fig. 8). These forms encroached on the floodplain area of flat relief as vast sandy landforms. According to Setmajer (1973), outflow of some flood water occurred along longitudinal depressions between the sandy bars. These forms may be therefore interpreted as overflow channels. Locally, stagnation planes were formed in shallow depressions between the levees and sandy bars as a result of the accumulation of mineral material. On the other hand, strips of the land in places where dead channels of the Vistula occur and which were located at the back of the levee at the base of the escarpment of the Pleistocene terrace, were functioning as typical back swamps. Peatbogs developed in these places, which formed planes of biogenic accumulation. This rich selection of landforms on the floodplain was

also supplemented by escarpments of sandy bars adjacent to the undercut banks of the Vistula.

The concave forms in the area of the Vistula floodplain described above are presently indiscernible because of the deposition of cultural layers. Some convex forms, on the other hand, are still clearly visible in the relief of central Kraków.

Taking into account the parameters of the analogous river meanders, until the 13th century the River Vistula had a width (*w*) of about 70 m and mean depth (*d*) of about 2 m. It was a winding channel (sinuosity = 2.0) with two well developed meanders with a radius (*r*) of about 400-500 m (Fig. 8). This value is similar to the radius (*r*) of the analogous meanders of the Vistula which occurred in the first part of the 19th century, before the river regulation works commenced. The reconstructed limit of the Vistula meander upstream of Wawel Hill, preliminarily based on opinions from the literature related to historical facts, and then modified to include local environmental conditions, did not reach the western foot of the escarpment of the Pleistocene terrace. In this part of the study area, peat sedentation in back swamps occurred at some distance from the active river channel. The Vistula meander, with its narrow neck, created the possibility of excavating a cut-off in the location of a probable flood overflow (Setmajer, 1973) as a result of the intentional actions of the Kraków inhabitants after 1257 (Radwański, 1975). If the shape of the meander was thus, the Vistula could not have flowed close to the western foot of Wawel Hill.

Downstream of Wawel Hill, the Vistula flows along the borderland zone between the Kraków Landbridge and Sandomierz Basin, where the valley widens (Fig. 1C; Fig. 7) which enables the river to divide into separate arms (Fig. 8). In the study period, and also later, the Vistula flowed in two channels: the southern one was the main channel and it showed a course similar to the present river course, and the northern one was a secondary channel and might have been silted up in the 13th century according to Mitkowski (1955). It is possible that the entrance to this channel might have been blocked by channel bars. The long section of the northern Vistula channel was formed as a meander similar in size to the meander located nearby (Fig. 8).

Discussion

One of key elements in the discussion on the relief of the Kraków area before the development of settlement on this terrain, is the evaluation of this area in terms of settlement development as early as in prehistoric times, in early medieval times (i.e. before the establishment of Kraków in the mid-13th century), and in the later period. So far there has not been a detailed analysis of this aspect, although the influence of land topography, and the distribution of wetlands and flooded areas were indicated by some authors (e.g. Łuszczkiewicz, 1899; Bąkowski, 1935; Dobrzycki, 1953; Mitkowski, 1955, 1957; Żaki, 1962; Jamka, 1963, 1971; Radwański, 1972, 1975; Tobiasz, 1977). In a historical analysis, attention has been paid below to some aspects of the relationship between the preurban relief of Kraków and the development of settlement.

The location of early-medieval settlement noted in documents is centred within the boundaries of the contemporary centre of Kraków (Fig. 1D) (Radwański, 1975; Atlas Historyczny Polski, 2008) and this correlates with the distribution of landforms described in this area. The most significant is the distribution of landforms rising above the former vertical limit of flood water. Lower located areas on the floodplain, especially wetlands with stagnant water or peatlands, covered most of the study area until the end of medieval times (Fig. 9). Vast sandy bars, especially ones located at the eastern, back-end, part of the limestone hills, were rarely flooded. Much more favourable for settlement and defensive reasons were the plateaux of limestone hills surrounded by steep, locally rocky slopes, which towered 10-40 m above the vast wetlands. The most favourable conditions for the development of settlement

occurred on the spur of the Pleistocene terrace which was attached to Wawel Hill and bordered by a 7-10 m high escarpment, as it was beyond the limit of the flood water (Figs. 8-9). This area, surrounded by wetlands on three sides, was extremely favourable because of the defensive motivations behind the development of settlement in the area of pre-establishment Kraków in early medieval times (Radwański, 1975). This area lay adjacent to places utterly useless for settlement purposes, such as water pools, peatlands and also places containing wood macro-remnants deposited during floods (Figs. 8-9).

The prehistoric settlement recognised in the study area comprised Wawel Hill and Lasota Hill. In early medieval times other large hills were inhabited. The largest settled area was on the spur of the Pleistocene terrace, where numerous centres of settlement developed since at least the 8th century. An early Kraków town composed of settlements established under Slavic law formed on this terrace, and the first churches in Romanesque style were built from the 10th century onwards. Simultaneously, the Royal Castle and Cathedral were extended on the fortified Wawel Hill. At that time churches were also built on the eastern part of Saint Bronisława Hill, named Salwator, and on Lasota Hill. Early medieval settlement was also found the highest located areas within the Vistula floodplain (Fig. 10) (Radwański, 1975; Atlas Historyczny Polski, 2008).

In 1257, the boundaries of Kraków established under the Magdeburg law were delimited on a densely populated area of the spur of the Pleistocene terrace (pre-establishment Kraków), and the boundaries of Kleparz Town nearby in 1366. On vast sandy bars within the Vistula floodplain, the boundaries of Kazimierz Town were defined in 1335 (Fig. 10). The development of these towns in medieval times, together with extended Royal Castle and Cathedral on Wawel Hill, formed the main agglomeration in former Poland. Roads joining the settlement centres were set out this way, so as to go across the wetlands using the possibly shortest routes. In a similar manner, roads were laid out joining the early Kraków with all the regions of Poland and with neighbouring countries (Fig. 10) (Atlas Historyczny Polski, 2008).

The authors explain their views concerning the occurrence of some landforms. These forms had to be clearly identifiable in the field during the period analysed and these were either not mentioned in earlier papers, or their limit of occurrence was suggested differently. The occurrence of some landforms described in earlier papers should also be questioned.

The landforms, which have not so far been taken into consideration and which are visible in the former topography of the centre of Kraków, include the limestone hill located NW of Wawel Hill and a hill located SE of Skałka Hill (Fig. 8). The first of these is masked by younger deposits and buildings, and the second was dug out at the turn of the 18th and 19th centuries when a limestone quarry was set up in this location (Radwański, 1975). The former occurrence of these hills is demonstrated by the limestone outcrops marked on geological maps (Gradziński, 1972; Rutkowski, 1992, 1993) and local land elevations marked on maps of the 18th and 19th centuries (Atlas Historyczny Polski, 2008). In addition, some historical references (literature citations in Radwański, 1975) and the traces of such forms which are still visible imply their former occurrence.

In addition, there is also no more detailed information in the literature on the lower fragments of Wawel Hill and Skałka Hill which were formed as flat areas and covered with Vistula alluvia. The explanation of the origin of these forms as the result of tectonic thrusts of about 20-30 m (Kmietowicz-Drathowa, 1964) of the side sections of horsts, as suggested by the geological profiles of this part of Kraków (Kleczkowski & Myszka, 1989; Rutkowski, 1992, 1993), is insufficient. It is more probable, according to Kmietowicz-Drathowa (1964), that these are erosional platforms surrounding Wawel Hill and Skałka Hill, which is indicated by their location around limestone hills (which have a circular plan) rising

above the topographic surface (Setmajer, 1973). Additionally, taking into account the location of these hills in the immediate neighbourhood of the Vistula river, one should also consider a fluvial-denudation origin of these flatnesses. These forms are fossilised by overlying alluvia 5-15 m thick. These erosional platforms may indicate the original horizontal limit of the plateau parts of the horsts, which, due to long-enduring undercutting by the Vistula (at least since the beginning of Quaternary), were reduced to their present size.

The authors agree with Radwański (1975) and refute the possible occurrence of two fossilised channels of the Vistula in the centre of Kraków in the southern section of the spur of the Pleistocene terrace, which according to Mitkowski (1955, 1975) could have joined two meanders before the 13th century (Fig. 3B,C). Such a situation is excluded by the fact that there was a 7 m height difference between this terrace and the floodplain and also because of the geology of the southern part of the Pleistocene terrace where tectonic horsts occur under a thin cover of anthropogenic deposits. The most recent papers still refer to these former views. The authors, taking into account the former height of the southern part of the spur of the Pleistocene terrace, agree with Radwański (1975) that before the 13th century the course of the Rudawa river towards the east across the Old Town was not possible. The Rudawa river could only have approached from the west as far as this spur of Pleistocene terrace and joined the Vistula upstream of Wawel Hill.

The authors, including the opinion of Setmajer (1973) concerning possible late-Quaternary routes of the Prądnik river which flows towards the present northern limit of the Old Town, do not exclude the possibility that erosional cutting of the Pleistocene terrace developed so forming a ravine, which was then fossilised under a cover of anthropogenic deposits. Jamka (1963) suggested the occurrence of two such cuts reaching a depth of 8 m and totally covered by deposits in the western part of the Old Town and its environs. Such deep erosional cuts in this part of the study area were rejected by Radwański (1975), based on the height of the primary soil roof measured in a dense network of measuring sites. Taking into account the distribution of the contour lines of the primary soil roof in this part of the Old Town based on Radwański's data (1975) (Fig. 5), the Authors suggest a depth of erosional cuts covered by cultural deposits not exceeding 3 m.

In the beginning, the occurrence of the Vistula meander upstream of Wawel Hill up to the second part of the 13th century was either questioned by some authors or not included in their papers (comments in the papers of Kmietowicz-Drathowa, 1965; Radwański, 1975; Tobiasz, 1977). Only in the publications of Humnicki (1979) and Niezabitowski (2007) did that former meander of the Vistula start to be treated as a fact. Radwański (1975) and Niezabitowski (2007) indicated that this meander did indeed occur in the past based on historical guidelines. They obtained information from historians on the curved course of the early medieval route joining pre-establishment Kraków with the Czech Kingdom. This route passed around the above-mentioned meander of the Vistula river and neighbouring wetlands, and through Salwator on its way to Prague (Fig. 10). Radwański also gave information about the intentional cross-cutting of the meander neck by the inhabitants of Kraków after 1257 and the building up of a levee in this location. If that is the case, the cutting across a narrow meander neck should be recognised as a task requiring less effort at that time. Excavation works were facilitated by the natural lowering of the ground which developed in this part of the meander during large floods (flood spillway), and which may be seen in Setmajer's map (1973) (Figs. 7-9). The supposed suggestion may therefore be put forward in relation to an advanced stage of development of the Vistula meander upstream of Wawel Hill. Radwański also mentioned the opinion of historians with regard to the lower run of the Rudawa river which flowed in the cut-off meander of the Vistula, later called Nieciecz (in Polish "not leak") and the opinion of the local population

reflected the smaller amount of water flowing in this section of the former Vistula channel.

Analyses of historical maps and drawings also suggest the former existence of the above-mentioned Vistula meander. The analysis of maps in the Historical Atlas of Poland (2008) shows a curved course of the lower section of the Rudawa river, which was preserved until the end of the 19th century, and which may be interpreted as imitating the former Vistula meander. This section of the Rudawa river, which flows in the wide bottom of the former Vistula channel, shows a very meandering course seen on the maps of the early 19th century. Most of the area of the former Vistula meander has been used as pastures and grassland since at least the 16th century. The other part was built-up, e.g. on the levee area along the River Vistula. There are, however, no high buildings in this part of the town and in general, the undeveloped area along the former Vistula meander represents a green area in Kraków. The maps and panoramic drawings of Kraków included in the Atlas mentioned above show where the northern limit of the Vistula meander could have been located. This area consisted of street villages, like Czarna Wieś, which curved and bordered pastures to the north. These pastures are still undeveloped and form recreation areas for the town. The western limit of the Vistula meander may only be reconstructed to the south of the eastern end of Saint Bronisława Hill (Figs. 8-10), where a palaeochannel is marked on topographic maps of the 19th and beginning of the 20th century. Its course is integrated with the general plan of the meander.

Since the 1950s, there has been a problem associated with the determination of the eastern limit of the Vistula meander under study, i.e. towards the Old Town. Opinions diverged (Fig. 3B-D). Even the newest version of the extent of the Vistula meander should, according to Humnicki (1979) (Fig. 3F), be scrutinised because the course of the Vistula is shown too close to the western edge of the Pleistocene terrace, and, according to Radwański (1975), peat deposits over 3 m thick occur at the foot of the terrace. This fact excludes the possibility of the course of the Vistula so close to the Old Town. This fragment of river meander should be shifted to the west. The route proposed by the Authors for the limit of the Vistula meander upstream of Wawel Hill is shown in Figs. 8-10 and is linked to the meander course suggested by Humnicki (1979).

The run of the northern arm of the Vistula downstream of Wawel Hill in the 11th-12th centuries was shown by Humnicki (1979) to be even closer to the edge of the Pleistocene terrace (Fig. 3F). Peat deposits occur on the floodplain (Radwański, 1975) to the east of the spur of this terrace. The run of this arm of the river, which has formed a meander, should also be moved away from the escarpment of the Pleistocene terrace – in this case towards the south. The lie of this arm of the Vistula until the 13th century, as suggested by the authors and referred to in the opinions of other authors (Mitkowski, 1955, 1957; Żaki, 1962; Radwański, 1975) is shown in Figs. 8-10. It is possible that the Vistula channel and its meanders in the Kraków area showed that, until the 13th century, other parameters were important for the analogous channels/meanders functioning during the first half of the 19th century. At the end of the Little Ice Age and due to the extreme deforestation of the Carpathians in the 19th century, the river regime changed in comparison with the 13th century, which could have resulted in shallowing and widening of the channel and an increase of the meander limit even before the beginning of regulation works. In the 13th century, the Vistula channel could have been narrower and deeper, and the meanders could have been smaller than has been assumed based on an analogous situation at the beginning of the 19th century. It is not possible, however, to estimate these changes.

The following facts, exceeding the timeframes of the work, indicate periodic changes in the functioning of the Vistula river which flowed in two channels in the exit zone from the Kraków Landbridge. Development of the secondary channel of the Vistula in the form of a meander, required a long period of time,

at least several centuries (Trafas, 1975, 1992), much earlier than the mid-13th century. This may indicate the former main river flow in this arm. Later, between the 13th and 17th centuries, the secondary channel changed into the main channel (see maps included in Atlas Historyczny Polski, 2008), possibly due to intentional action on behalf of the inhabitants of Kraków, who aimed to keep the river close to the town (Radwański, 1975; Tobiasz, 1977). In turn, the former main channel became silted and changed into a secondary channel (Atlas Historyczny Polski, 2008) (Figs. 9-10). Between the 17th and 19th centuries, the roles of the channels reversed again and the channel with the meander became silted up and was buried in the 1870s (Tobiasz, 1977).

Conclusions

The results of the investigations are based on information on the area in the centre of Kraków originating from different spheres: archaeology, history, geoengineering and geomorphology. Some information was difficult to obtain and some was not published. The opinions shown by the Authors, especially on maps and figures, represent the first attempt to make a synthesis of the knowledge hitherto held concerning the relief of the centre of Kraków before the mid-13th century. Because of scattered information and often divergent opinions, the formulation of statements must have been critical and often based on the contemporary morphology of other sections of the Vistula river. At present, the recognition of the topographic surface covered by cultural deposits in the study area in the centre of Kraków and, based on archaeological and geoengineering investigations, should be recognised as being sufficient. Further discussion on the former relief of this area, i.e. before the rapid development of the town in the 13th-14th centuries, may only be connected with other interpretations of the facts.

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