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Historical anthropogenic layers identification by geophysical and geochemical methods in the Old Town area of Krakow (Poland)

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ABSTRACT

In the Middle Ages, trade and craft started developing intensely in Krakow, a significant metropolis of Central Europe. This led to a considerable demand for water, which resulted in the creation of an elaborate network of artificial watercourses. Their course, until today, has not been sufficiently studied. Non-invasive geophysical methods combined with a small diameter borehole drilling technique and geochemical analyses can identify the presence of structures connected with historical moats, millstreams, etc. on the basis of historical sediment recognition. The research carried out in 2010 involved measurements with two geophysical methods, i.e. the ground-penetrating radar (GPR) and the cesium magnetometer. Due to the high attenuation of electromagnetic waves by anthropogenic soil and magnetic disturbances connected with a tram line, additional measurements were undertaken using the electrical resistivity tomography (ERT) technique. This method allowed the detection of structures buried under anthropogenic layers. Based on the use of borehole drilling and the acquisition of ground profiles, it was possible to present a more precise interpretation. In consequence, the location of historical watercourses was determined and the course of their fragments was mapped more precisely. The measurement of the basic physicochemical proprieties of the ground samples (pH, Eh, EC) and determining the metal concentration with atomic absorption spectroscopy (AAS), enabled to identify anthropogenic-origin metals, such as Cu and Pb, and also those of the geogenic origin, like Fe, in the medium. The measured values were correlated with the measurement results of magnetic susceptibility, which allowed for lithological classification of the layers.

1. Introduction

The main aim of this research is the identification of the earth of the Krakow Planty Park substratum. The present study is the continuation of the investigations presented in a publication from 2010 (Wardas-Lasoń et al., 2010). In that paper, the research team used the ground penetrating radar (GPR) method and geochemical methods to determine the location of a small fragment of a historical moat at the outlet of Wiślna St. in the Krakow Old Town. Later, in 2012, the range of methods applied in the investigations was broadened both in the field and in laboratory surveys (Łyskowski and Wardas-Lasoń, 2012). Magnetic measurements (with a gradient cesium magnetometer) as a supplementary method for the GPR measurements were also verified (Łyskowski, 2011). All the above mentioned experiments allowed for the elimination of time-consuming and ineffective methods and the selection of the adequate parameters for future measurements. As one of the such was the magnetic method, which due to magnetic disturbances connected with debits of bricks in first partly loose earth-and-rubble accumulation layer, and a nearby passing tram line. As an extension of previous works, and also as a continuation of the city geoarchaeology study, the scope of research was broadened and was complemented with electrical resistivity tomography (ERT) measurements and, again, with non-invasive GPR measurements using antennas with lower frequency for more accurate mapping of the buried deeper layers. However, during the surveys presented in this paper, also the GPR method showed ineffectiveness. Probably such results were connected with the high scattering of EM wave in anthropogenic layer and attenuation of EM wave in watered moat sediments. On the basis of those measurements, sites for borehole drillings were indicated. From the geological works which were carried out, earth samples were collected and the lithological profile was created. Geochemical analyses were made and then compared to the magnetic susceptibility values of each samples.

The results of the research on the use of geophysical methods in archaeology were presented in a collective publication edited by Furmanek et al. (2016), entitled "Geophysical Methods in Polish

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Archaeology". This interesting compendium, containing archaeological and geophysical prospection cases, was assisted by an analysis of geochemical properties. A study similar to the research presented in this paper was described by Lintern et al. (2016). The authors determined the location of historical layers through dating them with ^{210}Pb and ^{137}Cs isotopes. In the study presented by Sokołowska et al. (2016), a relationship between sewage production and the presence of sediment layers in the medium was investigated. The changes in magnetic susceptibility parameter of the soil over the four-year period were measured. The existence of a strong correlation between the magnetic susceptibility and the concentrations of Fe_2O_3, Zn, Al_2O_3, MnO was shown, which was explained by the phenomenon of the absorption of these heavy metals into ferromagnetic minerals. A similar study, with a combination of geophysical methods supplemented by lithological recognition, is presented by Moscatelli et al. (2014). This study was based on > 200 boreholes, 24 electrical resistivity tomography (ERT) profiles and a dozen of GPR profiles. The collected data allowed for precise characterization and determination of the presence of historical archaeological layers. It was possible to generate depth-slice maps of the resistivity anomalies positioning the location of archaeological artifacts. Another example is the paper by Tsugai et al. (2014) where, with the use of GPR, researchers characterized and distinguished layers of an archaeological site, including the presence of water sediments. This work was also supplemented with information obtained from boreholes. The last example, very close to the scope of the present investigation, is the paper by Jarzyna et al. (2012), where the measurements of magnetic susceptibility of the Main Market in Krakow showed a contrast between the values of this parameter in anthropogenic layers and in the natural layer (virgin sands).

2. Study area and history

For many years, Krakow was the centre of trade in Central Europe, and it also was the Polish capital city. The development of the city itself allows for distinguishing eight principal periods in its history. The beginnings of human settlement on the terrain of Krakow can be assigned to the period between the decline of the older Pleistocene era and the 7th century, concurrent with the period of the Vislane state (Wisła, i.e. Vistula, the main river in Krakow). The time between the 7th and 10th centuries is recorded in history as a tribal period, but also as the time of belonging to the Czech Duchy, and maybe to the Wielkomorawskie Duchy, as well. The end of the 10th century brings sovereigns of the Piastowie lineage to the city, and elevates Krakow to the rank of the main political centre of the young Polish state in 11th century. The period until the 13th century, is called przedlokacyjny – pre-fundation settlement, organized settlement under new laws. The spatial and legal location of Krakow takes place in 1257, under the Magdeburg Law, and it is an unquestionable turn in its history. The rest of the 13th and 14th centuries witnesses an unusual demographic and economic growth of the city (Niezabitowski, 2008). Approximately a dozen open settlements existed in the foreground of the two great defensive settlements surrounded by powerful wood-earth ramparts reaching about the height of several metres. Their existence served ancilliary and production purposes (Zaitz and Zaitz, 2008). The diversity of the terrain surface, more visible then that it is today, facilitated extending the defensive system and helped in the development of a net of natural and artificial watercourses.

Krakow lies on three individual morphostructural units: the Cracovian Upland, the Sandomierska Valley and the Carpathian Foothills, clipped with the hydrographic knot of the Vistula, Rudawa, Prądnik and Wilga rivers. On this basis, Krakow was called the trade emporium of Central Europe (Pociask-Karteczka, 1994).

Mapping the history of the changes in the location and the condition of the watercourses in Krakow solely on the basis of written records is not possible. In various periods between 12th and 19th centuries, they were transformed and adapted to the needs of citizens and local crafts. These needs resulted from the demand for drinking water for people and animals, the need for filling the fish ponds, but also from the form of industrial activities – particularly during the period of the rise and functioning of the institution of the Great Scales (weigh house called Great Scales, polish name Wielka Waga), where metal was divided and traded. The unit of sale in the 14th century was a plate weighing about two cetnars (126 kg). In the 16th century, the main merchandise produced by the craftsman was lead oxide, which was made from waste resulting from the silver cupellation process. The portioning of material at the Great Scales did not serve only far-reaching trade but it also met the needs of the regional markets, because lead was used in building, the metallurgy of noble metals, artistic craft and weapon production. Lead oxide (litharge, polish name glejta), was used in the process of pottery glazing, glass production, painting and the production of coins (Schejbal-Dereń and Garbacz-Klempka, 2010). The region of the Great Scales became contaminated, and through washing out and mechanical dissipation of the contaminants it was a significant source of their emission. Metals dissolved and fused with the particles of the ground and migrated deep into the substratum and, with the process of surface run-off and by means of sewage collectors, they reached the watercourses and water reservoirs of the city. Finally, this caused the contamination of the millstreams which were the sources of drinking water, distributed with the use of piling up devices, the so-called rurmus or rurhaus. Consequently, this problem caused the necessity of cleaning millstream beds. The network of water supply in Old Krakow existed till 1655, when the Swedish invasion devastated the city and its infrastructure, which the citizens never managed to reconstruct. In the years of 1822–1830, Planty Park were created and beneath them the old moats, ponds and millstreams were buried with their high sanitary and heavy metal contamination. The Rudawa was redirected from the town to the former, old bed of the Nieciecza river, which was regulated and shortened in the second half of the 19th century. In the years of 1907–1912, the Nieciecza was directed trough the former millstream of the Norbertanki monastery (at St. Bronislawa Hill). The upper fragment of the Rudawa, running from Mydlniki, is now dry and its middle and lower sections have also been buried. The present bed of the Rudawa has been rebuilt within the city area. The Prądnik river has also been regulated. Both these rivers propelled numerous mills and filled many ponds with fresh water (Pociask-Karteczka, 1994). The effects of these historical transformations of the water network in Krakow were further influenced by the quick and expansive territorial development of the city at the decline of the 20th century (Niezabitowski, 2008).

3. Methods

The surface investigations included scanning the medium with a ground penetrating radar (GPR). Based on electromagnetic wave (EM) propagation, this method registers differences in the amplitude value of different geological or anthropogenic structures in a time domain [ns]. The EM wave is reflected at the boundaries of each layer present in the medium, but also during the propagation it is attenuated and scattered. The full description of the methodology and the interpretation method can be found in many sources, e.g. Annan (2001) or Reynolds (2011), and also in Łyskowski and Wardas-Lasoń (2012) and Wardas-Lasoń et al. (2010), to which the present work refers. For the purposes of this study, unshielded 200 MHz and shielded 250 MHz antennas were used.

The applied electrical resistivity tomography (ERT) method belongs to the group of geoelectrical methods of engineering geophysics. This method has proved to be the right choice in numerous archaeological investigations (Furmanek et al., 2016; Łyskowski et al., 2016; Moscatelli et al., 2014; Gołębiowski et al., 2014; Pasierb, 2012b). It utilizes the phenomenon of electric current flow through the investigated, inhomogeneous medium. ERT measurements are carried out in a single process controlled by the measuring instruments on several dozen electrodes (48 pcs in this case study) distributed over the entire length of the profile spaced at the same distance. During the