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CHEMICAL AND PHYSICAL PROPERTIES OF SOILS AND SEDIMENTS

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Declaration

I hereby declare that this submission prepared under the guidance of my supervisor at the Faculty of Philosophy and Arts is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another neither person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of any university or institute of higher learning.

In Pilsen, April 23, 2018

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1. Introduction

Ancient human settlement had undisputable effects on the environment, many of which can still be recognized after long periods of elapsed time. Anthropic changes can be observed in various forms and on different scales. Foraging societies already had strong impact on local geomorphology and soil chemistry, which can be seen in the most conspicuous form on the example of shell middens (Erlandson 2013). With the growing escalation of artefact production and rising complexity of our societies, the human influence on the environment is undoubtedly measurable in ice cores and sedimentary archives (Lawrie 1999), presenting anthropogenic contamination and pollution of air, water and soil. Urbanization, landscaping, formation of synanthropic ecosystems, and grand engineering projects of ancient civilizations have changed the natural properties of the environment on ever increasing scale (Delile et al., 2015). Today it is well recognized that human action, both in prehistory and in the present day, has massive impact on soils, and that these actions result in changes that can be analyzed in numerous ways (Wells and Terry 2007, 285–290).

Several disciplines have, over the course of years, become more involved in studies of soil and sediments related to prehistoric human settlement activities. Soil chemistry and physics have come to play a progressively more significant role in this research. The improvement of analytical techniques has enabled a kind of “crime scene archaeology,” where disciplines such as environmental archaeology, geoarchaeology, archaeopedology, and others take part. It is becoming more easily to acquire chemical and physical bulk data by a multitude of analytical techniques. This enables collection of large amounts of data. Nonetheless, reference materials are needed to theoretically and practically understand these data obtained. Reference material stands here for an umbrella term, covering traditionally managed cultural soils or archaeological site active long enough to bring about a change in the soil and sediment compared with a background soil (Linderholm 2007). Since it has been noted (Lutz 1951; Cook and Heizer 1962, 1965) that numbers of chemical elements were enriched in anthropic soils, element analysis has been repeatedly used and is now a well-established practice in archaeology (i.e. Fleisher and Sulas 2015; Davies et al. 1988; Holliday and Gartner 2007; Linderholm 2007; Salisbury 2013; Scott et al. 2016; Terry et al. 2004; Wells 2004; Wells and Terry 2007; Wilson et al. 2008, 2009). The relationships between particular activities and the elemental indications they produce are not fully understood and need to be better established even though it has been possible to detect the activity concerned on occasion (Middleton 2004).

Questions, that archaeologist repeatedly addresses in site studies concern site-formation processes, stability of habitation, use of space, type of prevailing economy, and ways of social organization regarding the areas of activities. Many of these questions could be at least indicated on the basis of results of geoarchaeological research. Chemical and physical analyses of soils will result in variation that clearly cannot be entirely related to prehistoric human settlement activities. The geology and geomorphic setting at a site and developments of soil formation also contribute to heterogeneity of analyzed data in a given landscape. Various factors have to be taken into account while assessing and interpreting chemical and physical data. However, absolute understanding might not always be necessary to address archaeological questions to be answered. What is more essential is that the prehistoric phenomena under investigation must possess a durability that yields a measureable change (Linderholm 2007).

The general aim of my thesis is to establish and broaden the general knowledge of geochemical and geophysical properties of soil and sediment concerning archaeological research and the importance of their significance. More specifically, I attempt to describe the importance of numerous chemical elements, bearing greater or lesser archaeological value and various specific methodologic approaches of both geochemistry and geophysics addressing the archaeological problems. The majority of methods described belong to most well-known geoarchaeological methods frequently used at the present day.

Preparation of this master´s thesis is closely related to the archaeological investigation of Plzeň-Hradiště (Fig. 1) (Šmejda et al. 2013; Šmejda 2014, Šmejda et al. 2015), which took place mainly in 2012 and 2013 under the guidance of PhDr. Ladislav Šmejda, PhD., who is happen to be the supervisor of this thesis. Within my thesis I describe this archaeological investigation in detail together with the environs and setting of the site. A number of non-destructive geoarchaeological approaches were applied to the extent of the site and are further described and discussed. I set out here to combine results some of these methods to arrive to the conclusion how are the chemical elements spatially distributed at this particular site and if some meaningful patterns can be identified in the data and if there are some site areas, that can be convincingly classified into certain groups with similar chemical characterizations.

The aim of my research was (apart from broadening of knowledge of geochemical and geophysical approaches applied to archaeology) to answer the following questions:

1) Can the large-scale mapping of the elemental composition of the upper layer of contemporary soil be used for the detection of ancient settlement activities at Plzeň-Hradiště?
2) Which elements, in addition to P, indicate ancient settlement activities and seem to be the most useful in the conditions of this particular site?
3) How much is the concentration of different elements affected by recent and modern interventions to the extent of Plzeň-Hradiště site? Could a geoarchaeological preliminary survey determine the subsequent course of an archaeological research and help to clarify state of the archaeological site from the point of view of the protection of the historic monuments and protected spaces?

2. Geochemistry and geophysics in archaeology

Chemical and physical properties of soils and sediments are able to answer many specific environmental and archaeological questions (Dupoey et al. 2002; Hejcman et al. 2013, 287; Salisbury 2013; Šmejda et al. 2017). Analyses of such properties should be an important part of archaeological investigations, for they can make a contribution to our knowledge about the site´s sediments formation and visualize the area of a human impact and subsequent taphonomic transformative processes. If studied with necessary caution, they can be examined by statistical tools and/or visualized in terms of their spatial distribution over the entire studied space and therefore help to answer the queries made.

2.1 Geochemistry in archaeology

Understanding the spatial patterning of human activity is of a crucial importance to the interpretation of any archaeological site. A well-defined stratigraphy is not developed at every site and not every site is endowed with a sufficient material record that can be used to shed light on the past activities and how these were spatially distributed. In such cases geochemistry can provide an effective solution for examining the use of archaeological space.

The core principle behind archaeological geochemistry is that human activity causes chemical distortion (enrichment or depletion) to the local substrate (Mikołajczyk and Milek 2016, 577; Oonk et al. 2009 with references). During decomposition of organic waste oxygen, carbon and hydrogen escape as gases or liquids; calcium, chlorine, sodium and nitrogen form easily soluble compounds, sulphur combines with hydrogen to hydrogen sulphide and escapes. On the contrary, phosphorus, iron and silicon may bind with the geological soil substrate (Kuna et al. 2004, 531). Although we can see the increasing interest in multi-element mapping of archaeological soils (Terry et al. 2004; Fleisher and Sulas 2015; Šmejda et al. 2017, 2017b), the determination of phosphorus (P) concentrations remains the most important issue in many cases, although the archaeological significance of other elements has been studied in various geographical and cultural contexts (Oonk et al. 2009; Wilson et al. 2008; Šmejda 2017b, 62). Detection of archaeological structures is generally based on the patterning of postholes and hearths. Together with these features, diffuse greenish yellow or reddish soil colorizations have been witnessed within and around such structures (Steenbeek, 1983, 1984; Hessing and Steenbeek, 1992). These features are evidently unconnected to excavation of post-holes or trenches in the past, but are supposed to result from phosphate rich manure inputs and might indicate livestock-holding. Larger evidence on the cause and formation of these soil colorizations however has not been reported yet (Oonk et al. 2009). Other elements which are known to indicate past settlement activities are calcium (Ca) and magnesium (Mg). Accumulation of Ca and Mg on archaeological sites is linked to the use of Ca and Mg rich clay sediments for the construction of buildings, deposition of mortar from the destruction of buildings and to the deposition of biomass ashes and bones (Hejcman et al., 2011, 2014; Salisbury, 2013; Šmejda 2017b, 155). A handicap of Ca and Mg for archaeological prospection is their susceptibility to leaching so they modify their concentration after deposition. Additionally, analyzing Ca and Mg concentrations in order to recognize human activities is problematic on substrates naturally rich in Ca and Mg. Another significant element is potassium (K) which accrues in archaeological sites mainly because of the use of K rich clay sediments for the construction of buildings and the deposition of biomass ashes and faeces (Hejcman et al., 2011). In the ion form, K is also released particularly rapidly from clay minerals (Hejcman et al. 2013, 186). Losses of K with leaching need to be known for accurate balancing, especially on coarse textured soils, where K can be a critical element (Kayser et al. 2012). Zinc (Zn) and copper (Cu) are microelements present in plant and animal biomass (Hejcman et al., 2011). In acidic soils, Zn is susceptible to leaching, but in Ca rich soils with alkaline soil reaction, Zn losses are marginal. Unusually high concentrations of both components in soils and sediments can indicate mining and metallurgical activities of nonferrous metals (Horák and Hejcman, 2016). Sulphur (S) has received so far very little attention from the archaeologists. Sulphur is an essential macronutrient required for plant growth (Maruyama-Nakashita et al. 2005). In plants and animals, S is found in the amino acids cysteine and methionine, and therefore in proteins, in many cofactors and prosthetic groups, peptides such as glutathione, in sulfolipids, sulphated polysaccharides, and many secondary metabolites such as glucosinolates and alliins (Kopřiva, 2015). Sulphur cycling in ecosystems is faster than the cycling of P, therefore the S enrichment of archaeological soils does not remain as high over a long period as the P enrichment (Šmejda et al. 2017b, 63). These elements are taken up by plants and, through food by animals and they have been found in elevated levels in archaeological sites where plant and/or animal tissues and their ashes are deposited (Fleisher and Sulas 2015, 59; Wilson et al. 2008). Other elements (e.g. Al, Cr, Co, Ni, Pb, U) can concentrate in archaeological contexts connected with burning, food processing, and the occurrence of metal and/or metal-bearing resources such as pigments and tanning salts (Fleisher and Sulas 2015, 60). Apart from degraded organic materials, anthropogenic mineral inputs are also likely to play a significant role in feature formation. Additionally, Al, Fe and Mn-oxides are essential because of their large quantity in most soils (Stipp et al., 2002) and reactivity towards many (in)organic soil constituents (Fortin et al., 1993; Sugita and Marumo, 1996; Tessier et al., 1996). As a result, soil feature development and formation is expected to be affected by the oxidation state of metals in soils, the mineral forms in which these metals occur, their crystallinity and level of cementation (Sugita and Marumo, 1996). Due to the continual accumulation of anthropogenic elements to the soil during occupation, mineral precipitation may also be important in feature formation (Oonk et al. 2009).

2.1.2 Overview of related geochemistry methods

Various methods to study elements in archaeological soils and sediments have been developed and used under laboratory or field conditions, ranging from simple qualitative colorimetric P analyses to quantitative multi-element analyses of selective chemical soil extracts using inductively coupled plasma spectroscopy and X-ray fluorescence spectroscopic analyses of bulk soils (Oonk et al. 2009, 37). Applying of these methods has brought varied results in terms of element composition of anthropogenic soils and the data are often disputable (Mikołajczyk and Milek 2016, 577; Oonk et al. 2009). In many cases it remains ambiguous if this variation is affected by a method applied (e.g. regarding to soil sampling, samples pretreatment, analyte extraction and analysis itself) or a sample-effect (e.g. related to environmental conditions, soil and sediments type, archaeological background, natural geochemical modification). Therefore, the interpretation and assessment of data obtained remains a challenge. A better understanding of the influence of the archaeological setting, site lithology and physical-chemical soil environments on the chemical fingerprints of human occupation is needed. Methodological standardization will enable comparison of data and improve the applicability of soil chemistry to solve the archaeological questions (Oonk et al. 2009, Wilson et al. 2008. 2009).

The following geochemical methods count among the most ubiquitous archaeology-related methods and were used during the archaeological investigation at Plzeň-Hradiště hillfort or could have been used for the purpose of investigation of similar archaeological sites.

Phosphorus analysis

As already mentioned, determination of phosphorus (P) concentrations remains the most frequently applied soil analysis in archaeology. P is a major archaeological indicator among pre-agricultural and agricultural archaeological societies, for its sensitivity and persistence. Another factor, which makes P a suitable marker for geoarchaeological study is that anthropogenic P can exist in the pH range of most soils. Under acidic condition, P combines with iron and aluminum, whereas under basic conditions, P combines with calcium (Holliday and Gartner 2007, 303).

O. Arrhenius (1931, 1935) noted as the first scholar that the accumulation of P can be detected in the stratigraphic sequences of archeological sites (settlements) in the southern Swedish region of Skåne. W. Lorch (1940) employed Arrhenius´ knowledge and developed further methods of P analysis (Majer in Kuna et al. 2004, 215). The development of phosphorus analysis and its numerous methods has been described in detail in a vast amount of literature on the topic, thoroughly summarized by P. H. Bethell and I. Máté (1989), Vance T. Holliday and William G. Gartner (2007), Sherburne F. Cook and Robert F. Heizer (1965). More references and information can be found in these sources.

Soil P chemistry is very complex and phosphorus is articulated across the soil horizon in the form of many different chemical compounds (Stevenson 1986, 245 categories in detail). There are many classifications of soil P and depictions of soil P cycle. The nomenclature and even the categorization of P forms vary significantly (Holliday and Gartner 2007, 303). Occluded P refers to orthophosphate ions that have become physically incorporated or chemically entrapped within particles, generally clays composed of amorphous hydrated oxides of iron and aluminum or amorphous aluminosilicates (Holliday and Gartner 2007, 303). P is a part of some well-known phosphate minerals: wavellite [$Al_3(PO_4)_2(OH)_3.5H_2O$], vivianite [$Fe_3(PO_4)_2.8H_2O$], dufrenite [$FePO_4.Fe(OH)_3$], strengite [$Fe(PO_4).2H_2O$] a variscite [$Al(PO_4).2H_2O$]. The concentration of soil P is lower in sandy soil (although some phosphate compounds are relatively stable, the tension to leaching and transformation of P has been recorded in sandy soil), and rises in soils rich in calcium (Janovský, M. 2015, 11).

Anthropogenic P accumulation is explained by the deposition and decomposition of urine, excrement and organic refuse (Sjoberg 1976, 448) and resembles the past human activities. With prolonged occupation of the site the accumulation of anthropogenic P at site may become quite large in comparison to the content of P in the natural soil. P is mainly cycled in a geological time while many more elements are cycled much more rapidly. Added P quickly bonds with Fe, Al, or Ca ions (depending on local chemical conditions, particularly pH and microbial activity). Some forms of soil P are highly resistant to normal oxidation, reduction, or leaching processes. Ash from fires, burials and different fertilization techniques ranging from burning and the use of "green manure" to application of guano and human waste cannot be forgotten while considering the accumulation of anthropogenic P (Holliday and Gartner 2007, 302).

P may be extracted from the soil in numerous ways. Likewise estimating the P content in the extract can be achieved by various chemical analytical methods or even chemical-physical procedures. This fact led understandably to segmentation of different P analysis modifications when each of them has its own advantages and disadvantages and restrictions. There are in total approximately 50 P analysis methods and about 30 of them have been used for archaeological purposes. For further information, detailed listing and references see Holliday and Gartner 2009, 309; Robert C. Eidt (1973, 1977), W. I. Woods (1975, 1977) a B. Proudfoot (1976). Speaking about our geographical area, since 1976 A. Majer (1984, Majer in Kuna et al. 2004, employed e.g. by Ernée 2005) has been developing his own method of P analysis, using acetic acid of 5% concentration. Also L. Págo (1963), J. B. Pelikán (1955) and M. Soudný (1971) have contributed to development of P analysis methods.

Archaeological soils can be treated by different extractants starting with water, allowing determination of concentration of elements in the soil solution. The use of the Mehlich 3 (M3) extraction solution (composition: 0.2M CH_3COOH + 0.25M NH_4NO_3 + 0.013M HNO_3 + 0.015M NH_4F + 0.001M EDTA; usage: 25 cm_3 reagent per 2.5 cm_3 soil, Mehlich 1984) has been employed at Plzeň-Hradiště site. M3 solutions is classified as weak extractant, so it is effective at measuring the so-called plant-available P, which is the fraction most easily affected by man rather than the P tied up in hardly soluble minerals such an apatite and fixed in Ca, Fe and Al phosphates (Terry 2000; Hejcman et al. 2013, 180). M3 extraction procedure is the official agro-chemical method for testing the forest and agricultural soil in the Czech

Republic and is extensively used in Canada, USA and Slovakia (Hejcman et al. 2013; Novák et al. 2013; Kuncová and Hejcman 2009, 2010; Abdi et al. 2010; Hejcman 2011, 2012a,b, 2014).

pH analysis

The pH of a deposit measures its alkalinity or acidity on an inverse logarithmic scale broadly relating to hydrogen ion concentration on a scale from 1–14. pH less than 7 is acid, more than 7 alkaline, and pH 7 is neutral. Because the scale is logarithmic, a shift of pH of 1, for example, from pH 5 to pH 4 represents a 10-fold change in acidity. Most soils have pH in the range 2.5–10 with plant growth optimized at pH 5–8. Also most soils in arid and semiarid environments tend to have a basic pH value, which means pH > 7. In contrary most of humid environments soils tend to have rather neutral to acidic pH values, especially near the surface thanks to organic acids residues. The pH is a measure of hydrogen ion activity in a solution. Although activity and concentration are not the same, pH can be thought of as a measure of H^+ concentration, more precisely as the negative logarithm of H^+ concentration expressed in moles per liter: (Balme and Paterson et al. 2014, 60-61)

$$pH = -\log [H+].$$

The soil pH measuring is a primary control on preservation and development of a site, reflects many chemical and physical properties and can provide a broader understanding of the formation soil processes through the time. pH may asses soil´s fertility, guide options for further in situ conservation at a site and show probabilities what proxy data could be present in deposit sequence, for example, absence or presence of pollen, diatoms, or phytoliths (Fraysse et al. 2006, 2009). Soil pH is a key determinant how minerals move into solution and it is a reflection of solubility of metals and nutrients availability. All of this leads to the fact that the soil acidity influences the reliability of phosphate analysis (Kuna et al. 2004, 532; Holliday and Gartner 2007, 306 is more detailed). Human interactions with soil may also change the pH values. Agriculturally modified soils should have different pH values from nearby soils which have never been cultivated; however the change in pH spectrum will vary with local conditions. Biogenically induced shifts due to earthworm secretion are also reflected by pH (Canti 2006).

It is important to know that pH values of soil can change relatively rapidly as a response to changes in soil environment. pH values measured today may significantly vary from those which could the soil evince in the distant or recent past as the soil has developed through the time. pH prevailing at the time of deposit formation could be different when we consider that some human activities as for example adding manure to the soil change pH intentionally. The measured pH may also vary across diverse sections of excavation or deposit.

Soil pH is usually estimated either by colorimetric or electrometric methods. The colorimetric method is based on the fact that certain organic materials change color at different pH values. Indicator solutions, for example, phenolphthalein and methyl orange, can be used to determine pH, as can strips of paper coated with such solutions (e.g., litmus paper). Colorimetric methods can be useful in the field but are not as precise as electrometric methods (Balme – Paterson 2014, 62). Hence, these methods could be used only for primary orientation and are not suitable for executing geochemical measurements for their small distinction and precision.

The electrometric method is based on the fact that the concentration of H^+ is proportional to electrical potential. A pH meter is actually a modified voltmeter which converts pH into electrical potential since changes of pH influences the changes of electrical potential of specific electrodes immersed into solution. The rise of pH value with one unit results in growth of electrical potential for 58.15 mV in the environment with temperature of 20°C, measured against reference electrode which does not reflect the change of pH and its electrical potential is stable. This kind of measurement is dependent on stable temperature, mostly around 20°C. Modern electrometers are equipped with devices eliminating the temperature effects. More detailed information to electrometric methods in M. Kuna et al. (2004, 207-210) and J. Váňa (1984, 259-279). When reporting pH results it is important to state the employed method and if known, parameters like the nature of the material, that is what is contributing to H^{+}, soil and solution ration, content of salt in solution and soil, the temperature of the soil solution, carbon dioxide content and errors associated with equipment calibration.

X-ray fluorescence (XRF) analysis

X-ray fluorescence analysis has similar characteristics as atomic absorption spectrometry and optical emission spectrometry. The exception is that the sample does not need to be dissolved in a solution to be analyzed successfully. Fluorescent X-rays waves are electromagnetic waves created when irradiated X-rays force inner-shell electrons of the constituent atoms to an outer shell and outer shell electrons quickly travel to inner shells to fill the vacancies.

Created fluorescent X-rays retain energies characteristic for each of chemical elements. These energies detected by the device detector enable the qualitative or quantitative analysis.

Portable X-ray fluorescence (pXRF) is a portable form of elemental analysis instruments based on X-ray fluorescence technology. X-ray fluorescence (XRF) spectroscopy (e.g. Beckhoff et al. 2006, Jenkins et al. 1995, Jenkins 1999, Hevesy 1932) is a well-established and commonly used technique in obtaining diagnostic compositional data on geological samples. Lately, progresses in X-ray tube and detector technologies have resulted in miniaturized, field-portable handheld instruments that allow new applications both inside and out of standard laboratory settings (Young et al. 2016). Portable X-ray fluorescence analysis presents an attractive opportunity in the chemical characterization of archaeological soils and artifacts so the specialist can promptly analyze specimens without the need to remove a sample from the artifact. Recently, it has been confirmed (Rouillon and Taylor 2016, Šmejda et al. 2017, Young et al. 2016), that the pXRF provides for some elements high-quality data, comparable to laboratory XRF devices. Nonetheless, there is a trade-off. There is a necessity as with all XRF devices to use matrix-matched standard reference material to obtain reliable, calibrated results (Hunt and Speakman 2015).

Particle size analysis

Particle size is a stable soil property. Particle size analysis or grain size analysis belongs to the packet of useful tools of modern soil science. Distribution of particle size is very important since it assesses the level of soil formation and spots imbalances in soil profiles (Vranová et al. 2015, 1419). The granularity of soils may show the potential differentiation of cultural layers and natural sediments (Kuna et al. 2004, 524). The roundness and sphericity of sedimentary particles also record distinguishing characteristics of origin, depositional history and transport agent (Hunt 1989, 45). The differences in the sedimentary particles size and particularly the absence of fine clay components can fundamentally change the ability of soil to bind phosphorus (e.g. highly acidic soil, in addition soaked with water because of the grain size, is more likely to wash out phosphates.). The grain size forms a size range continuum from fine clays (generally <2μm or <4μm), silts (2 or 4 μ to 63 μ), medium and fine sands (500–63 μ), coarse sand and very coarse sands, (0.5 mm–2 mm, i.e., 500–2000 μm) granules/gravel (2 mm–>1024mm), coarse cobbles and boulders. For practical purposes, however, they are broken into main four categories (Goldberg and Macphail 2006, 337):

1. The coarse or stony fraction (granules/ gravel, stones/pebbles, cobbles, and boulders)

2. sand,

3. silt

4. clay.

Nonetheless, the grain size range varies in compliance with use in geological engineering, geology or pedology and causes extensive and divided methodologies of estimating grain size and grain distribution. Various particle size systems are used in different countries, which complicate a comparison between samples originating in various locations.

Frequently archaeologists deal with deposits that contain a multitude of different grade sizes that are <5 cm. In such cases, one is not evaluating individual grains but rather populations of different grains or soil texture. The overall texture of a deposit can be assessed in the field by adding water to a small sample and estimating plasticity, stickiness, and grittiness, in other words “finger texturing” by hand (Balme and Paterson et al. 2014, 58).

The most and traditional basic method for estimating two different size populations, mostly sizes of sand and stone compounds is through a combination of sieving and settling analysis. Employing of wet or dry sieving usually requires a larger soil sample about 1 kg. The sieves are systematically folded up by the decreasing size of standardized mesh.
Sediments dominated by sands are estimated by dry sieving of fully disaggregated sediments, usually disaggregated by means of mortar and pestle. Sandy sediments dominated by clay and silts may be analyzed by wet sieving in order to separate silt and clay from the sand content, however this analysis demands a chemical pretreatment (i.e. hydrogen peroxide (H_2O_2) mixed with deionized water) to eliminate the organic matter or chemical dispersants such as sodium hexametaphosphate (Calgon). The chemical pretreatment and drying of sample add processing time (more references in Kuna et al.2004, Balme and Paterson 2014, Goldberg and Macphail 2006, Lisá and Bajer 2014).

More precise determinations of fine clay are usually made in sedimentary laboratories. On the present day it is preferable to use laser diffraction analysis (Šimek et al. 2014). The laser granulometers scales mostly range from 0.04 μm to 2 mm. Laser light scatters the dispersed sample in a sediment/water mixture (suspension). Laser ray goes through the turbid suspension and enables the measurement of particular grain size and suspension density. Laser diffraction (Kadlčák 2014) has the benefit of automation and simple manipulation with the device, however, effectivity of measurement depends on the degree of overall ideal dispersion of particles. The dispersion in KOH supported by ultrasound is commonly employed. So called total dispersion involves removal of calcium carbonate and organic constituents. It eliminates the “noise” from organic and calcium carbonate matter, which would distort the primary sedimentation matrix. Laser diffraction is suitable for small and fine-textured samples and has the ability to analyze their particle size distribution (Lisá and Bajer 2014).

The traditional method known as “pipette method” (discussed in detail by Janitzky, 1986) employs the Stokes´ law. The soil samples are chemically pretreated to remove organic matter and soluble salts. Sample is then dispersed in the sodium solution in the sedimentation cylinder. The basic principle of the analysis is that spherical particles will settle in fluid at a rate proportional to their radius. The speed of settling is dependent on temperature. Sediment is removed in a specific time interval (commonly from 30 seconds to 8 hours) from a certain depth of the sedimentation cylinder, dried and weighed. The volumes of particular fractions are calculated subsequently.

2.2 Geophysics in archaeology

Historically and traditionally, geophysics has been a discipline used to characterize large-scale and deep structure of the Earth and for petroleum and mineral exploration (Witten 2006, 1). Geophysics applied to archaeology has dramatically enhanced its importance over the past decades. It is a non-destructive way of surveying archaeological remains, features and buried structures. Geophysical archaeological methods use some principles and methods of applied geophysics but it is important to note that there is no single method, which could perform optimally at all sites and for all applications and situations. Each method has its strengths and weaknesses and exploits different physical principles and material properties of buried structures. Feature invisible to one method may be detected by another approach. The various geophysical techniques for identification of the subsurface features all depend on differences in various physical properties of sediments and rocks: electric, magnetic, thermal, seismic etc. Individual techniques may be classified as passive or active. Magnetic, thermal and gravity measurements fall in the first category. The significant attribute of the first static category is the fact that the existing physical fields are measured directly without instrumentally generated signals. Static techniques exploit forms of naturally occurring energies constant over time. In the second or active category, the instrumentally created signals pass through or bounce/reflect from the subsurface feature and are then detected and recorded. Seismic techniques, soil resistivity, electromagnetic technique and ground-penetrating radar are all active devices (Weymouth and Huggins 1985, Witten 2006).

There are numerous archaeological geophysical techniques and the proper and careful selection of the particular method on the basis of anticipated target is important. Among the most known archaeological geophysical methods we count metal detector. Potential targets are metal objects, historical period sites, battlefields. Soil electrical resistivity can detect near surface features, rock features, houses, pits, mounds, hearths. Sump features, pits and houses, trenches and metal object might be also surveyed through the means of electromagnetic conductivity. Ground penetrating radar is used for detection of voids, tombs, coffins, cellars, foundations, grave shafts and cisterns. Another well-known geophysical method applied to archaeology is magnetometry and through its application we have much valuable information about subsurface anomalies, trenches, houses and pits and wells and foundations. Magnetic susceptibility is usually applied in habitation zones, hearth areas and middens (domestic waste and other artifacts and ecofacts associated with past human occupation). For summaries and more references to the most geophysical methods and suitability of their use see i.e. Aitken (1974), Tite (1972),Witten (2006), Kuna et al. (2004), Křivánek (1998a, 1998b, 2002a, 2002b, 2002c), Křivánek and Gojda (2002), Křivánek and Kuna (1995), Sala et al. (2012), Goldberg and Macphail (2006).

The overall effectivity of archaeological survey is influenced by many factors (Kuna et al. 2004). The adequate difference of the archaeological subsurface features and their physical measurable values from the bedrock and other archaeological situations is of significant importance. The buried features or stratigraphic units in situ must be preserved in sufficient extent, amount and orientation. The generally intensive trend of landscape changing through the human interaction often does not allow profitable application of geophysical methods. A very distinctive factor complicating the employment of geophysical methods may be a rough terrain relief and its thick vegetation cover. The absence or at least a clear distinction of recently emerged subsurface features is of key importance while being focused on a specific archaeological situation. Characteristics, thickness, homogeneity and type of the soil cover or horizons at the site affect the efficiency of archaeological geophysical survey. Knowledge of regional geology including the geological processes, mining and quarry areas may lead to the recognition of problematic zones concerning the application of geophysics. For magnetometric or geoelectric measuring, the vicinity of a watercourse or groundwater level can have a disturbing impact on obtained data. For geophysical surveys based on measurements of magnetic field it is important to avoid the proximity of high-voltage power lines, electrified railways, and a mere occurrence of metal object and active quarries and hectic transport infrastructures. Especially while employing the electromagnetic and geoelectric methods the stability of climatic conditions at the measured and evaluated site is essential. Casting a glance at numerous limiting conditions for application of geophysical methods to archaeology it seems that in certain regions it might be very complicated to find a suitable site or area for geophysical examination. It is true in most regions with high population density and developed infrastructure, as well as in the industrial landscapes.

2.2.1 Overview of related geophysical methods

As mentioned earlier, methods for identification of past human occupation areas has developed rapidly over the past decades. Especially the ability to distinguish anthropogenic from background signatures, where only a little surface evidence exists, has improved profoundly. The geophysical properties of soils and sediments have been used to recognize the activity areas at some archaeological sites in a non-destructive approach. Currently there is a number of available such methods. The non-invasiveness as a key advantage is achieved through ground penetrating radar (GPR), that emits radio waves and the detected reflectance of subsurface signatures enables to examine sediments, floors and prepared surfaces (Goldberg and Macphail 2006). Electrical resistance methods operate by passing an electrical current through electrodes sunk in the soil. The measured and detected differences in electrical resistance may reveal boundaries between materials and their depths. Magnetometry can detect perturbations to the Earth´s magnetic field over a ground surface and buried archaeological artifacts and material, especially those relating to heating activities, (e.g. hearths, ditches and pits) can contribute to this pattern (Walkinghton 2010).
A widespread method, related to examination of magnetic properties of soils in an archaeological context, is magnetic susceptibility. The magnetic susceptibility is measurable both in field and in laboratory premises.

The following geophysical methods listed count among the most well-known archaeological prospection methods and were used during the archaeological investigation at Plzeň-Hradiště site (Šmejda 2014, 249) or could have been used for the purpose of investigation of similar archaeological sites. Most methods were used at Plzeň-Hradiště in a spatially limited sample with the exception of caesium magnetometer, which was successfully applied on the whole extent of the enclosed settlement and meadow adjacent to the site to the north.

Electromagnetic survey

Electromagnetic methods (EM) have been applied extensively in agriculture and metal detection (Sala et al. 2012). There has been a general absence of studies published on EM employment in archaeology in the past two decades. Although they used to be very popular in the past, EM survey techniques have fallen out of favor among archaeologists, since they decided to rely on alternative techniques such as ground penetrating radar, magnetometry and electrical resistivity (Bigman 2012, 31). Despite some of the method´s drawbacks, the EM still offers a various advantages such as possible survey in diverse environmental conditions, ground cover and speed in data collection. C. Gaffney stated (2008, 327), that this technique remained underused. In the recent years, there has been an increase of published studies relying on EM methods (Johnson 2006, Perssona and Olofsson 2004, Witten 2000). The EM technique is predominantly effective in typifying the nature of the soil material (such as texture, moisture and organic matter content) and of some categories of man-induced soil alterations (bricks and metal) (Saey et al. 2015), burned soils and artifacts and detecting caves, tunnels and other voids (Witten 2006, Křivánek in Kuna et al.2004). Electromagnetic measurements are influenced by several factors; such as material properties, shape and size, orientation of a conductive object and compaction/porosity (Witten 2006).

The most electromagnetic surveys applied for archaeological purposes use the so-called "slingram" set up with a continuous-wave, low-frequency transmitter–receiver pair (Gaffney 2008, 325). The slingram configuration allows measuring simultaneously of both electrical conductivity and magnetic susceptibility (Thiesson 2009, Saey et al. 2015, Bigman 2012). The essential principles of EM induction method are Ampere´s and Faraday´s laws. Ampere's law states that when electrical current streams through a coil of wire it creates a magnetic field that is perpendicular to the plane of the coil. Faraday's law states that when a conductive object is positioned into a moving magnetic field, a current will be induced in that conductive body (Bigman 2012, 31). In its simplest configuration, an EMI soil sensor consists of two coils separated by a given fixed distance. A primary magnetic field is created by an alternating current in the transmitting coil. This field exposed to the soil causes electrical currents (eddy currents), which induce a secondary magnetic field. Primary and secondary fields induce an alternating current in the receiving coil (Saey et al. 2013, Bigman 2012).

Enhancements and advancements in instrumentation and data collection methods now allow surveying by means of EMI in a relatively short period of time (Bigman 2012, Gaffney 2008).

Magnetometry

Magnetic survey has been for a long time a source of successful cooperation between archaeologists and geophysics. Le Borgne (1950, 1951, 1955, and 1960) investigated several hundreds of soil and sediment samples from around the world and he observed that the uppermost few centimeters of soil have much higher magnetic susceptibility than the underlying bedrock. He concluded that the magnetic enhancement is very nearly universal and is largely independent of bedrock lithology (Evans & Heller, 2003). The effect of fire has been shown of great importance. The advantage of using magnetic techniques to describe the magnetic fraction is that the entire sediment or soil sample can be examined without prior separation (Dalan et al. 1998). Magnetometer examinations belong to the most effective and universal techniques among the geophysical approaches used for archaeology because numerous archaeological entities have distinctive magnetic properties which allow one to distinguish them on the surface of the site by the particular magnetic abnormalities they form. Magnetometry techniques measure the Earth´s magnetic field (across the ground surface) (Goldberg and Macphail 2006). While employing the magnetometry techniques it is highly advisable to avoid igneous areas and scattered metallic debris. Hearths and burned areas are detectable. Trees and thick vegetation impede survey. The detection of contrasts in the magnetic properties of different materials is the core principle of this method. Most of the iron is dispersed through soils, clays and rocks as chemical compounds, which are magnetically very weak (Smekalova, Voss and Smekalov 2005). Human activities in the past, particularly those involving heating, changed these compounds into more magnetic forms. The ultimate outcome of these activities is the production of highly magnetic maghemite (γ-Fe_2O_3) from weakly magnetic hematite (α-Fe_2O_3). Hematite is reduced to magnetite (Fe3O4) when the above vegetation is being burned, the soil is moist and the anaerobic conditions are prevailing. In course of subsequent drying or cooling, the anaerobic conditions are reestablished and allow reoxidation to maghemite (Evans and Heller, 2003). These more magnetic forms build patterns of anomalies in the Earth´s magnetic fields. Special instruments – magnetometers are able to detect these anomalies and bring to light more information about the subsurface archaeological features and objects (Smekalova et al., 2005). Magnetic anomalies within the Earth’s magnetic field are instigated either by induced or remanent magnetism. Induced magnetism indicates that an object within the earth’s magnetic field come to be magnetized by the act of the Earth's magnetic field on it. Remanent magnetism describes the magnetism that an item has in the absence of a magnetic field. During heating, specific small regions known as domains reorient themselves. While cooling there is a tension to the aligning of these domains more or less in the direction of the existing Earth´s magnetic field. Thus, they are parallel to each other and create a net magnetization. This net magnetization is fixed with respect to the object. Both types of magnetism are of great importance in archaeology.

The remanent magnetization relating to the effect of heating could be as much as ten times greater than the induced magnetization. Archaeological features and objects such as kilns, fire places, slag blocks and furnaces evince strong traits of remanent magnetization (Goldberg and Macphail 2006, Smekalova et al. 2005, Křivánek 1999, Křivánek in Kuna et al. 2004). The induced magnetization is directly proportional to the strength of the ambient field. A property called magnetic susceptibility, æ (or κ), is the ability of a material to boost the local field. The magnetic susceptibility of a soil or sediment is given by the quantity of magnetic minerals present (Goldbergh and Macphail 2006). Additionally, the occurrence of magnetic bacteria (Fassbinder et al. 1990) as a noteworthy contribution to enhanced magnetic levels related to rotted wood has shed light to the post-built structures and timber circles in magnetometer data records (Neubauer 2001; David et al. 2004).

Magnetic susceptibility is given not only by the quantity of magnetic minerals present, but also by nature and grain size of the sample. It is defined as the ratio of the induced magnetization to the inducing field, i.e., it quantifies the response of a material to an external (weak) magnetic field. It can be either expressed as a mass susceptibility (normalized by mass) or as a volume susceptibility (normalized by volume) (Dalan and Banerjee 1998, 6). Low frequency mass-specific magnetic susceptibility (expressed as χ_{LF}) is one of key laboratory techniques (Linderholm 2007) (Goldberg and Macphail 2006, 350). There are more magnetic room-temperature parameters to be measured (see Dalan and Banerjee 1998, Goldberg and Macphail 2006, Piper, 1987; Jackson et al., 1988; King and Channell, 1991; Hunt et al., 1995). The value of magnetic susceptibility decreases with depth. The great differences in this variable between the upper and lower soil layers concerning anthropogenically altered soils may be attributed to the abundance of an anthropogenic impact in the upper layers. Compared with lower horizons of the leached soil the difference can be high (Mermet et al. 1999). The first influence on magnetic susceptibility is a biological activity creating the magnetic mineral maghemite (as once described above), especially in top soils because of the "fermentation processes". This is associated with alternating reduction and oxidation environs. The second influence is burning, affecting the top layers of soils and sediments, causing iron minerals become aligned (this phenomenon is used for paleomagnetic assessing and dating of hearths) (Goldberg and Macphail 2006, 350). Magnetic techniques have been used for estimating appropriateness of sites for survey or to aid in the interpretation of the research results. More broadly said, it means defining site limits, activity areas and other features, studying the morphology or utility of these locations, areas and features and the associated processes responsible for their change and transformation. Also understanding of the processes of erosion and sedimentation may be improved through application of magnetic analysis. This method also helps to build and correlate stratigraphic sequences and complement climatic data and more information on regimes and modes, which form soil within archaeological contexts (Dalan and Banerjee 1998). They are also used for archaeomagnetic dating, material analysis, magnetic studies of lake or bog sediments and cores, studies of cave sediments and recognizing of paleosoils and associated palaeoclimatic data (Goldberg and Macphail 2006).

Georadar

Ground penetrating radar (GPR) is a geophysical method that is able to accurately map the spatial extent of subsurface objects, changes in soils and sediments or archaeological features and produce images of recorded materials (Conyers 2006a). Radar waves are emitted in certain pulses from a surface antenna, reflected off soil units, bedding contacts, buried objects and features and detected back at the source by a receiving device. As radar pulses are transmitted through various materials on their way to the subsurface features, their velocity changes depending on the physical and chemical properties of the material through which they pass (Conyers 2006, 136). Each moment the radar pulse strikes the material with a different composition or water saturation, the speed changes and a portion of the radar pulse is reflected back to the surface, where it is recorded by the receiving antenna. The remaining pulse continues further to reflect features buried deeper until it finally disappears? in the depth. The greater the contrast in electrical and to some extent magnetic properties of two materials buried underground, the greater the strength of reflected pulse and consequently the grater the amplitude of reflected signal, showing the different dielectric constant. The depth (or distance) of the subsurface feature is measured by recording travel times of each radar pulse (Goldberg and Macphail 2006). When their velocity is known, the measurements can be used to produce a three-dimensional visualization of the sub-surface situation.

The success of GPR survey depends on soil and sediment mineralogy, clay content, surface vegetation, topography, ground moisture and depth of burial. Situations to avoid while executing the GPR measurements are highly conductive clays, clays and salty rocky deposits. Trees and high grass impede survey and roots cause anomalies. It is not a method to be applied to any subsurface situation; however it can be employed for many different sites and their conditions. Although ground radar penetration and the capability to reflect the pulse back is enhanced in a dry soils environment, most of the soils and sediments can still transmit and reflect radar signal in the moist environment and the GPR survey executed under such conditions yields meaningful data (Conyers 2006).

Electrical resistance and resistivity

Electrical resistance is a macroscopic property and electrical resistance method belongs to a group of geophysical approaches which employs the electrical current. This electrical current is flowing through the ground and the resistance is measured. Various features and objects below the surface produce anomalies causing the differences in resistance measured (Gaffney 2008). Object and features under the ground may show lesser or greater resistance to flow of the current, causing high or low anomalies. High resistance anomalies could be caused by stone walls, rubble and hardcore, roads, stone coffins, lined cisterns and constructed surfaces, i.e. plasters. Low resistance anomalies are usually instigated by ditches, pits, gullies, graves, drains and also metal pipes and various installations (Gaffney and Gater 2003), however once excavated and later filled disturbances may be indicated by resistivity highs or resistivity lows depending on the water content and degree of compaction of the materials compared to the surrounding medium (Samsudin and Hamzah 1999, 482). Resistance measurements are given in Ohms (Goldberg and Macphail 2006). Resistance depends on both the shape and size of features and the material in which we measure the resistance.

Electrical resistivity is the microscopic property of a given material and describes how difficult it is for an electric current to flow through it. This geophysical method provides more realistic measurement since it takes into account only the intrinsic nature of the materials themselves. It is given in Ohm-meters (Gaffney and Gater 2003; Goldberg and Macphail 2006, 315). The measurement is made by placing certain number of electrodes (usually four) into the ground, through which the electric current is passed and the voltage drop is measured. The depth of investigation of resistance measure is directly conditioned by the relative position of electrodes injecting current and the electrodes recording the resulting deviations by its pass in the ground (Sala et al. 2012). Different spacing of electrodes and multiple measurement result to obtaining of several maps variations for each location. Situations to avoid while measuring electrical resistivity may be distinguished by very dry surface, saturated earth and shallow bedrocks. Trees and grass impede survey and cause positive anomalies.

Seismic refraction and reflection

The geophysical methods commonly encountered in archaeology are ground penetrating radar, magnetometry, and electrical resistivity tomography and low-frequency geoelectromagnetic methods. However, each of these methods may suffer some limitations of use under atypical condition of the site under investigation. The challenges given by peculiar conditions of a site lead to use of methods, which may be far more used in geology than archaeology and that is e.g. seismic refraction method (Karastathis et al. 2001) (Zeid et al. 2017; Zeid et al., 2016). In the recent years it has been employed at many archaeological sites under investigation i.e. (Karastathis et al. 2001)(Samyn et al. 2012). Seismic refraction method is a geophysical method that has been developed for investigation of shallow surfaces (Azwin et al. 2013). This method is also known as velocity gradient or diving-wave tomography. It has a vast importance in guiding intellectual inquiry in use of subsequent methods of archaeological investigations. Seismic techniques have a little use in detection of terrestrial archaeological features due to frequencies and power levels utilized. Nonetheless, seismic methods employed by maritime archaeologists have had a success surveying the underwater sites. In seismic surveying, the seismic waves are created by a controlled source and propagate through the subsurface. Sound at a sufficient level to produce a return echo is introduced to the ground or water. Seismic refraction measures the velocity of a returning echo; the seismic wave in terrestrial conditions is generated by an energy source such as metal plate struck by a hammer (Azwin et al., 2013)(Herz and Garrison, 1998). The typical seismic wavelength is given in the range of few hertz (Hz) to a kilohertz (kHz). The detection of returning sound wave is measured by geophone arrays. In the seismic refraction technique, the incident wave encounters the subsurface with various elastic properties. With reflection, the energy of a sound wave is subdivided into refracted and reflected components. Measuring the seismic refraction, the portion of a returning sound wave is measured by geophone array and the depth and refractor velocity could be calculated using the arrival times at the various, but equally spaced geophone arrays. Typical seismic velocities vary in sediments, sandy gravel horizon with prehistoric debris, bedrock strata etc. Differences in velocities may indicate intactness and weathering of the bedrock and fluctuating continuity and compactness in soil and sediment horizons. The best results gave the bedrock surfaces due to the low contrast in refractive velocities. Relatively spatially adjacent archaeological features such as floors, pavings, walls or circuit wall could be detected by seismic refraction. Various collapsed chambers, subsurface tunnels, tombs and other voids may be examined by means of this method.

The frequency of a returning pulse is used for measurement of seismic reflection. The seismic pulse is a pressure phenomenon and most of the models are built by P-, pressure wave and S components. S component is that part of the wave train that radiates orthogonally to the direction of the P wave. Changes in P and S components could tell us much important information about the depth and nature of geological strata (Herz and Garrison, 1998).
In the recent years the horizontal-to-vertical spectral ratio (HVSR) technique has been used. However, this method is widely used in geophysics in seismic microzonation studies. For archaeological purposes this method has scarcely been documented in literature (Zeid et al. 2017; Zeid et al., 2016). This method is based on the estimation of the resonance frequencies due to the occurrence of layers with increasing acoustic impedance. The peaks can be interpreted to obtain the estimated depths of the impedance contrast horizons (Bignardi et al. 2016).

3. Background

3.1. Site characteristics

The hillfort site is located in the cadastral area of Hradiště u Plzně in the central part of West Bohemia (map reference: UTM-WGS84: 49°42'50.82"N; 13°24'05.59"E), this location is also called “Pod Homolkou”. The ancient hillfort Hradiště lies approximately 250 meters north-east of the present-day settlement of the same name. It can be found on the top of the spur elevated ca. 20-30 m above the narrow neck of a big meander of river Úhlava (Šmejda 2014, 239). This spur is protected by steep slopes in the south-east and north-west. These slopes are hardly approachable because of the river Úhlava underneath them; however, the river was also the closest water source in the utmost distance of 100 m accessible through the gully from the meander in the north-west and south-west. The altitude of the highest point of the site comes up to 337 m above the sea level and the whole area is slightly sloping (Fig. 2). The

area of the site has elongated kidney-like shape and covers approximately 1.65 ha with a single line of enclosing rampart preserved to a varying height around its perimeter (Fig. 3). In the proximity of the enclosing rampart there used to be one massive rampart, which remained only partly preserved. On the eastern side, it might have been destroyed by road, housing development and erosion. Yet on the north, we can see a massive rampart still elevated up to 3 m above the inner surface of the hillfort and 7 m on the outer side above the meadows.
The outer rampart on the north-west in the present-day gardens of private owners is despite many devastating interventions still quite massive. It reaches 12 m of the width at its base and its elevation above the inner surface is still 2 m which had to be much more in the past. Various arrangements might be made in the past to slow the approach to the rampart and expose the enemy to attack from the rampart and here we can find the outer ditch that is until today approximately 15 m wide and 2 m deep. Nowadays is the top of the rampart elevated around 4 m above the bottom of the outer ditch. Towards the north-west is the ditch disrupted by a road; however the axe of the ditch is heading in the direction of the natural gully on the north-west.

At the northern side of the hillfort, the inner enclosing rampart is the most massive, reaching the width of 8 m, the inner elevation of 3 m and the outer elevation up to 7 m. On the north-west, just above the river, the rampart seems to emerge only as a sharp terrain edge hardly ever reaching the elevation of 0.8 m above the inner surface. As a consequence of a long-term ploughing of the hillfort interior, the terrain at the edge gradually rises in a modest terrain wave up to 10 m wide. Traces of fire resulting in a burned and partially vitrified rampart can be observed in the form of scattered debris 10-12 m downslope on the outer side of the terrain edge, which might be caused by the gradual creep of the sediments from the hillfort plateau. The significant evidence of a high-temperature fire could be noticed around the entire perimeter of the inner fortification. On the south and south-east the rampart can be seen again, the inner fortification is elevated up to 4-5 m above the outer side. The enclosing fortification creates here a tip-like shape; unfortunately, the rampart located here is completely destroyed by the only access path to the village Hradiště. Concerning the terrain configuration we cannot rule out the possibility of the outer fortification line in front of the southern tip. The sand quarries heavily ravaged the surface there (Fig. 4).

The location of the gate leading to the inner area is questionable. Both the inner and outer enclosing ramparts have been destroyed by a modern road construction at the north-east part of the site and probably at this location we can assume the existence of a former entrance. The massiveness of the fortifications in the closest vicinity supports this hypothesis (Šmejda 2013, 7-10).

3.1.2 Site environs

Geomorphological maps classify the site as a part of the Touškov basin, forming the northern part of the Plzeňská basin. The sunken area resulting from denudation consists mostly of Carboniferous siltstone, claystone, sandstone and plum-pudding stone, arcose and Proterozoic argillite (Demek et al. 1987, 513-514). The site geological base is formed by indurated basalts, basaltic andesites and their alkaline equivalents and tuffs and slightly metamorphosed indurated olistrostromes (Geologická mapa České Republiky 1:500 000, WMS service). The site covers a large expanse of brown earth (Tomášek 2000, map). The mean annual rainfall is 550 mm and the average annual temperature is 7-8°C. The geo-botanical reconstruction map indicates subxerofilic oak groves at the higher altitudes of the site and alder groves and riparian woodlands on the river banks. The site nowadays lies fallow. The surface site is in its majority covered by grass and some self-seeded deciduous trees (Šmejda et al 2013, 10).

3.2 History of research

The site has been known to archaeology for more than 150 years and since then a number of small scale surveys and excavations have been undertaken there. The earliest mention of the site comes from 1862, when the prehistorian F. Olbricht visited the fortified site together with a town counsellor Pecháček and found the remains of ramparts and few ceramic fragments (Sklenář 1992, 169). Later it was mentioned among the sites renowned for the presence of so-called “vitrified ramparts”, i.e. stones and destruction layers showing traces of intensive fire. The prehistorian L. Šnajdr explored the site and found a feature at the southern end of the inner rampart filled with numerous animal bones and fragments of decorated pottery vessels (Šnajdr 1893, 491). During the 20th century, two important archaeological excavations took place. The first of them was carried out by F. B. Horák, who also commissioned the first detailed plan of the site for the purposes of archaeology. He dug several trenches into the rampart at various spots. This plan and a drawing of one trench section are archived at the Department of Prehistory of the Museum of West Bohemia, Pilsen (Fig. 5 and 6). The finds discovered by F. B. Horák could be linked to two main periods of the site biography: the final Bronze Age and the late Hallstatt period. After the First World War sand started to be quarried from the old river terrace on the south-eastern part of the site while the rest of its surface continued to be used as fields. The rescue excavations in the sand quarry carried out by V. Čtrnáct in 1947 made a discovery of plentiful, chronologically important pottery. These findings represent the end of early Bronze Age or the transitional horizon between the early and middle Bronze Age (Jílková 1957, 41; Jiráň 2008, 84). The site has been added to the national list of the archaeological monuments in 1957. The extraction of sand has ceased and the large sandpit, which had destroyed at least 20% of the inner area, was eventually recultivated. At last, a modern contour plan of the site was made in 1975 by the surveyors of the Czechoslovak Academy of Sciences. Together with small collections of finds obtained by the field walking, this overview of the earlier research activities prior to the beginning of the 21st century is complete (Šmejda 2014, 241).

3.3 The recent field project

The past research revealed that we are dealing with a multi-period site protected by a massive fortification, which was destroyed at least once by a high-temperature fire. Many questions however remained unanswered (Šmejda 2014, 241). The new project lead by PhDr. Ladislav Šmejda, Ph.D., obtained between 2012 and 2013 new data in the field. Besides academic interests this excavation was used as an opportunity to train the students of archaeology in field methods and to raise the local public awareness of the cultural heritage in the close neighborhood (Šmejda 2014, 242).

Having used this new data set the project aimed to elaborate on the following research topics:

1) Genesis and development, redesign, reutilization and the end phase of fortification.

2) Types of construction and development of fortification over the prehistory.

3) Function of the enclosed settlements as a category of supra-community areas (cult and ritual, trade, production area, elite residence, military installation).

4) Studying artifacts of different levels of complexity and related ecofacts.

5) Research of archaeological formation and transformation processes and testing of new possibilities of archaeological field documentation using the natural scientific methods and digital technologies.

6) Reconstruction of large rock formations and study of sediments of adjacent gullies (Šmejda et al. 2013, 18).

The research described above was carried out within the scope of project 'Partnership for archaeology" (detailed information about all grants provided in Šmejda 2014, 251).

3.3.1 Non-destructive prospection

The first group of methods that were applied in advance at the excavations but continued to be consulted repeatedly in various stages of the field project include aerial reconnaissance and geophysical prospection. There were investigated changes in land-use and vegetation cover in the target area on historic aerial photographs taken in various decades of the 20th century. Very useful data were acquired by airborne laser scanning (LIDAR) (e.g. Krištuf and Zíková 2015, 18), allowing visualization of a detailed terrain model in geographical information system (GIS) (e.g. Krištuf and Zíková 2015, 40-100). This elevation model provides an excellent overview of the topographic setting of the site and the well-preserved features of its anthropogenic relief. A combination of various techniques of aerial survey offered a good description of the rampart and its state of preservation in various parts of the site, as well as the general geomorphology, development of vegetation cover and progressive urbanization of the surrounding area over the last century (Šmejda 2014, 242).

A number of geophysical methods were used in the field experiments in order to contrast their outcomes and usefulness in the specific conditions of the site. The following techniques had been tested: 1) electromagnetic induction, 2) magnetometry, 3) georadar, 4) electrical resistivity, and 5) seismic refraction. Most of them were used only in a spatially limited sample, with the exception of caesium magnetometer, which was applied on the entire extent of the enclosed settlement (having first removed most of the shrubs growing on the abandoned fields) and of the meadow adjacent to the central part of the site to the north. The results of geophysical survey show clearly the extent of the former sand pit that destroyed a large part of the site's interior in the middle of 20th century (the geophysics reveal that the maximal extent of mineral extraction was probably even larger than what was known from historic aerial photographs). The geophysical survey showed that the line of fortification consists of highly magnetic material, and such physical properties indicate that at least its uppermost layers have been affected by a strong fire along the whole of its surviving length (Šmejda 2014, 243).

3.3.2 Excavation in 2012

The main effort of this excavation season was devoted to elaboration of a section through the rampart of the northern side of the enclosed area. This part of the rampart seemed to hold the most of stratigraphic information and to be well preserved. It is well known that the man-made ramparts are often able to retain and accumulate significant amounts of sediments at

their upslope side, which would normally get destroyed by erosion, are removed downslope by gravitation and disintegrated (Šmejda 2014, 242-243). A space free of trees was chosen for a cutting trench. The final section excavated in 2012 reached the length of 16 m and the width of 2 m (Fig. 7). While the major part of work was accomplished in the first season, the section was prolonged outwards in the following summer 2013 to obtain as complete picture as possible of the stratigraphy of inclined destruction layers forming the outer foot of the massive rampart. With this extension, the section reached the cumulative length of nearly 26 m. In the central (highest) part the layers accumulated to a massive 4 m thick sequence, sloping down toward both ends, but more dramatically to the north, following the natural inclination of the bedrock, formed by the old surface of river terrace.
Such a depth of a heterogeneous stratigraphy causes the instability of the trench walls. Despite numerous wooden props and steel grids installed in the excavated section, the western upper part of the trench had to be widened because of its unstable and collapsible features (Fig. 8) (Šmejda et al. 2015, 29-30).

Although some difficulties due to instability of the excavated sections occurred, it was possible to adequately document the whole sequence of chronological horizons. The excavation followed the stratigraphic units, recorded them by textual description in a structured way, drawings (Fig. 9) and photographs. Some interesting details were also documented by photogrammetry, the control points being measured by a geodetic total station to get all the field data into Czech national geodetic grid S-JTSK. The section provided abundant archaeological evidence such as animal bones, charcoal for radiocarbon dating, soil samples and botanical macrofossils. The final extent of the cut through the rampart was documented by 3D laser scanning at the end of season 2012 (Šmejda 2014, 244; Šmejda et al. 2015, 29 – 30). The complete primary field documentation is archived at Department of Archaeology, Faculty of Philosophy and Arts, University of West Bohemia and Museum of West Bohemia in Pilsen and the Institute of Archaeology, Czech Academy of Sciences (Šmejda et al. 2013, 21).

Results of season 2012

The archaeological survey aimed its attention to the cutting trench through a northern rampart and revealed a very complex stratigraphy and new information about fortification development in the early stages of the site, i.e. already in the transitional period between the early and middle Bronze Age (17th-16th century BC) (Šmejda 2014, 245-248; Šmejda et al.

2015, 31-37; Šmejda et al. 2013, 37-39). The survey results also helped to better understand the old documentation of F. B. Horák from 1911, who named one of the anthropogenic stratigraphic units as the "original terrain". It turned out that there are at least 5 clearly distinguished chronological phases, two of them were completely unknown prior the new excavation.

The inferences of the project and the resulting chronological model are based on the documented stratigraphy within the scope of excavated cutting trenches. Similarly the radiocarbon dating (charcoal samples were successfully measured in Beta Analytic lab in Florida (http://www.radiocarbon.com) and typological analysis of pottery evidence were employed.
The following overview of known fortification phases lists archaeological periods as they were recognized from the stratigraphy and associated finds and the absolute chronology cited as the most probable calibrated dating intervals.

1) The transitional period between the early and middle Bronze Age (17th-16th century

BC)

2) Middle Bronze Age Tumulus culture (15th century BC)

3) Final Bronze Age Nynice culture (9th century BC)

4) Late Hallstatt /early La Tène period (5^{th} century BC)

5) The early mediaeval phase (9–10th century AD)

The first phase corresponds with the findings from the rescue excavations carried out in the former sandpit (Čtrnáct 1954). According to the results of the recent field project it is possible to claim that there existed already some kind of fortification enclosure already in the Bronze A2/B1 chronological horizon. Nonetheless a very interesting discovery was performed during the recent field research. Tumulus culture phase includes at least two rebuilding stages of the fortification and indicates a complicated system of palisades and a stone wall that later collapsed and created a distinctive layer of substantial blocks of basalt rock spread down the slope. The features of this cultural phase also display traces of devastating fire. This chronological phase was not found before at the site and it is a completely new finding. In the sediment layers deposited during the middle Bronze Age on the inner side of the fortification several small bronze objects were found. The objects included a globular pin with perforated head, a bronze spiral, a smaller bronze circle/ring and a piece of bronze alloy (Fig. 10, 11, 12, 13, 14, 15)(Šmejda 2014, 246; Šmejda et al. 2013, 63-65).

The final Bronze Age horizon deposited on top of the above-mentioned phases embodies only minor traces of stone construction. These architectural remains consist of river cobbles resembling a paved surface, which could have served as a foundation platform for some structure built of perishable materials. The hypothesis that some kind of rampart existed in this time is supported by a large amount of loose material, which rolled down the slope. Construction details of this fortification remain unclear due to the lack of preserved in-situ evidence. The possibility of deliberate destruction of the final Bronze Age enclosure and the subsequent reuse of its construction material in the late Hallstatt period for a new rampart should not be excluded. The accumulation of the sediments on the inner side of the fortification continued and several smaller ceramic objects and some charcoals were found. Remarkably, this layer was marked by F. B. Horák in 1911 as "the original terrain", the lower stratigraphic phases remained at that time unrecognized and it is very probable that he did not manage or even attempted to get deeper during his excavation.

Quite remarkable debris of the late Hallstatt fortification has preserved, which clearly disintegrated during a high-temperature fire. Frequent finds of "vitrified" and partially melted basalt rocks are clearly associated with this particular phase. It is almost certain that the older information reporting the vitrified ramparts at the site refer to this very horizon. An interesting pottery assemblage from the La Tène period has been found on top of the late Hallstatt horizon. The spatial distribution of fragments belonging to a single ceramic vessel could reflect a surface created by remains of disintegrated late Hallstatt fortification. The mentioned find of ceramic fragments of one late La Tène vessel suggests that the site was used in this period, but it was not fortified in this phase. The absence of provable traces of functional fortification is typical for many of the hillfort sites with settlement features; however the majority of data obtained comes from early La Tène period (Venclová 2008, 37).

The uppermost part of the rampart was unexpectedly dated to early Middle Ages according to two samples of radiocarbon dating. This was a surprising discovery since there has not ever been found any medieval artefact at the site. The radiocarbon dating executed in 2012 examined nine charcoal samples. All the samples were originally located in the rampart and taken from larger sections of beams, which the authors of survey assumed to be oak beams (Šmejda et al. 2013, 90).

3.3.3. Excavation in 2013

A part of the section through the northern rampart from the previous year was uncovered again and prolonged outwards to obtain a complete stratigraphy of inclined destruction layers forming the outer foot of the massive rampart. At the same time, the existence of a hypothetical original trench in front of a rampart was tested. None of the applied research methods revealed an existence of such a trench.

The latter stage of fieldwork focused on the area of a probable bailey on the north side of the site, especially on its northern noticeable edge. Several small test pits were opened here, in order to answer specific questions regarding the relationship of the settlement to the erosion gully in the north vicinity of the main fortification line and the dating of the northern leg of rampart (Šmejda 2014, 244). According to the previous surveys and aerial prospection, no traits of any elevated constructions and archaeological findings are known in this area. Shallow testing trenches and pits in the area of the north rampart brought no datable archaeological findings. One trench was excavated at the edge of a gully, where a possible linear anomaly running along the south edge of the gully was indicated by geophysics and aerial prospection. The fieldwork did not prove any existence of a trench or any other linear construction and excluded any form of enclosure. Nonetheless this section allowed examining of the natural gully development dynamics and the sediments accumulation. The gully could have been used by population of the site partly as a fortification element. At this particular spot the soil landfill originating in the 20th century was found.

The last group of testing pits was located in the nowadays private garden areas. Finally the results of the outer rampart excavation in its restricted extent showed only a homogenous composition of this feature without any traits of construction, charcoal or archaeological findings. Therefore the dating of this site part remains uncertain (Šmejda et al. 2015, 37-42). This is strikingly dissimilar to the situation on the main rampart line, where abundant archaeological evidence and stratigraphy units were remarkable. Thus it might be hypothesized that the eastern rampart´s "life history" differs from that on the main rampart (Šmejda 2014, 244-245).

4. Materials and methods

Within this study I have focused so far on geophysical and geochemical properties of sediments and soils in archaeological excavation generally, thus the general approach has been outlined. Various geochemical and geophysical methods employed by geoarchaeology were described. I chose these earlier described particular methods to be mentioned since they were used or could have been used over the course of archaeological excavations at Plzeň-Hradiště. Majority of the previously described techniques also belongs to a set of usually applied geoarchaeological techniques (e. g. Aitken 1974, Balme and Paterson 2004, Kuna et al. 2004, Gaffney 2008, Goldberh and Macphail 2006).

Although several geophysical and geochemical methods were applied at Plzeň-Hradiště site, most of the soil samples and data were collected only from a spatially limited area in order to contrast their outcomes and mainly utility in the specific settings of the site. Data for magnetometry and later x-ray spectrometry were collected in the entire extent of the enclosed settlement and some part of adjacent meadows. The more detailed description of techniques used at Plzeň-Hradiště follows and several data analysis are presented.

4.1 Spatially limited geochemical and geophysical analysis

Ph

Plant residues were removed from samples instantly after assemblage and the samples were then air-dried, grounded in a mortar, and sieved to 2 mm.
Soil Ph (KCl) was measured in a solution (containing 10 g of soil and 25 ml of solution) containing 1 mol.dm-3 of KCl. The mixture was stirred with a glass stick and left untouched for 24 hours. Prepared infusion was measured while constant stirring by a measuring combined electrode until the signal stabilization of this electrode, not less than after two minutes.

Soil Ph (H_2O) was measured in a suspension of 10 g of dry soil sample mixed with 25 ml of distilled water. Distilled water was boiled prior the pH estimation in order to eliminate dissolved CO_2 and then it was cooled to the laboratory temperature. Prepared infusion was measured as in the previous pH measurement described. The measuring electrode of pH-meter was in both cases calibrated to three different buffer solutions of values pH = 3.56, pH = 6.87 a pH = 9.18 of temperature 25°C. The samples were measured at the same temperature. pH analyses were performed by Ing. Jan Hrdlička, Ph. D. from University of West Bohemia, New

Technologies Research Centre. pH analyses were executed for the samples originating in the rampart cross-section.

Spectrophotometric Determination of Phosphorus

Two air-dried 0.500 g soil samples were processed in a M3 extractant for 15 minutes. The samples were centrifuged after extraction. From the liquid section 2 ml were removed to each of test tubes and 8 ml of extractant were added (solution of ammonium molybdate, sulphuric acid, ascorbic acid and sodium thiosulfate). After one hour the test tubes were immersed into double boiler of temperature 95°C for 10 minutes. After cooling to the laboratory temperature the absorbance of individual solution was determined. A spectrophotometer Hitachi-U 2012 was used. The phosphorus masses of samples were calculated from the individual absorbance values given. Spectrophotometric determination of phosphorus was performed by Ing. Jan Hrdlička, Ph. D. from University of West Bohemia, New Technologies Research Centre. Spectrophotometric determination of P was applied again only to the spatially limited area, which was the rampart cross-section.

XRF Analysis

XRF analysis measurement was performed using the highly sensitive spectrometer for wavelength-dispersive X-ray microanalysis by Bruker company. The samples of following stratigraphical units were tested: 1003, 1024, 1042, 1014, 2027, 2019, 2025, 2052, 2010, bed rock (more stratigraphical units' information to be found in the site report; Šmejda et al. 2013). The samples were put in the sample container with a detection diameter of 8 mm. The samples were then determined by a default method for unknown sampling. The measurement was performed in vacuum, using a 20 kV or 50 kV beam (i.e. beam generated by these voltages) depending on the element measured. The detection of radiation was detected by proportional or scintillation detector (depending on the element measured as well). The results of performed XRF analysis were given data in the form of weight percentage. XRF analysis of submitted samples was performed by Ing. Marcela Čekalová.

Electrical Resistance

Electrical resistance measurements were applied within the area of enclosed settlement area in spatially limited extent. The aim and reason for this was to avoid the damaged terrain of the then sand quarry. On the northern site section the application of electrical resistance technique was limited by very thick surface vegetation. Some stone and waste landfill also affected the final location of electrical resistance survey. The measurement was performed by RM-15 setup (Geoscan Research, Great Britain), which is used for detection of subsurface anthropic object containing stone construction. Symmetric electrode array configuration was employed in Wenner Electrodes array A0, 5M0, 5N0, 5B. While employing this configuration it is possible to detect only subsurface electrical resistance changes to a depth of 0.5 m. The density of measurement was 1x1 m (Křivánek 2013, unpublished report provided by L. Šmejda).

Granulometry

Particle size analysis was applied only in a spatially limited extent. Sampling was performed for limited amount of stratigraphical units. The analysis was executed by Doc. Lenka Lisá, Ph.D. The analysis was performed by means of laser diffraction particle size analyzer.

4.2 Spatially extensive soil analysis

Magnetometry

The aim of executed magnetometry analysis was to obtain the information about archaeological subsurface objects and relicts from the entire area of the enclosed settlement. The actual state of terrain itself, which had been clearly alternated through the time, was evaluated as well. The northern part of the plateau is covered by a thick vegetation layer making the magnetometry survey impossible. Also primarily, it was very important to keep on mind the existence of stone and waste clusters nearby the road. Stone and waste conglomerations affect the results of magnetometry survey. Magnetometric survey at Plzeň-Hradiště site was applied by means of five-channel DLM-98 ARCH magnetometer (Sensys, Germany); using a wheeled carriage and five fluxgate gradiometers with FMG650B probes. The magnetometry survey at Plzeň-Hradiště site was defined by a measuring net of 0.5 x 0.2 meters (Křivánek 2013, unpublished report provided by L. Šmejda).

pXRF analysis

Portable XRF data were collected in the entire enclosed settlement area and its vicinity after the conclusion of the main excavation, which took place in 2012 and 2013. The data collection was carried out during autumn season 2015 by PhDr. Ladislav Šmejda, PhD. Data were collected in a polygon (Fig. 16 and 17). The concentration of elements was determined using a portable ED-XRF (energy dispersed X-ray fluorescence). The analyzer Delta Professional by Olympus InnovX with Soil Geochem measurement mode was employed. This device is capable to register concentrations of an extensive range of elements from the periodic table (Mg–U). Each measurement was performed for the period of 1 min, the first 30 s using a 10 kV beam and the remaining 30 s using a 40 kV beam (i.e. beams generated by these voltages). The pXRF analyzer employed gives records in the form of weight percentage. The survey covered an area of 42.5 ha (Fig. 18, 19) (polygon area calculated in ArcMap 10.1 by "Calculate geometry" command), where 120 sampling sites distributed in an irregular grid were analyzed. Before each measurement, plant biomass was removed from the topsoil surface and the concentration of elements was measured directly on the soil surface. The position of each sample was logged using a handheld GPS unit Trimble Nomad in the WGS84 coordination system.

4.3 Data analysis

Speaking about electric resistivity measurements, the data obtained had been processed by means of Surfer software (Golden software) by R. Křivánek, who performed the measurements. The final visualizations of results were displayed by the means of ArcMap 10 software (http://www.esri.com).

The acquired magnetometry data were processed in the first place via Magneto-arch programme (Sensys) and subsequently adjusted and visualized in the environment Surfer programme (Golden software), combined again with ArcMap 10 software by R. Křivánek, the author of the magnetometry measurements.

Within this study I processed the XRF data from the later pXRF analysis provided to me by L. Šmejda. As together with the particular method mentioned above, the data were collected during the autumn 2015 by L. Šmejda himself. He measured after all 120 different spots over course of two days, one in October and the later in November. This data set provided to me in Microsoft Office Excel involves the coordinate information. I used different functions of Microsoft Office Excel to process the provided data in order to put them in the decreasing or increasing order according to numeric value, to find the average values of concentrations of each chemical element, to calculate their concentrations summed up altogether. Maps of the site extent, the map of sampling distribution, the maps of elements concentrations and density were constructed in ArcMap 10.1 software (http://www.esri.com). The Kriging tool included in the Geostatistical tools was used to create the interpolated map surfaces. The statistical analyses were performed using tools of Microsoft Office Excel 2010 and Statistica ver. 12.5 software (http://www.statsoft.com).

4.4. Results

In total, 120 samples measured over course of two days in October and November 2015 were examined by means of XRF analysis and for each one sample the concentration (given in a weight percentage of a sample) of following elements was measured: Mg, Al, Si, P, S, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, As, Rb, Zr, Sr, Ba a Pb. These elements were detected in a larger or smaller amount in each of the soil samples, which gives us exactly 120 values for each one of elements, 2400 various concentrations of chemical elements in total (see the database on the attached CD). Percentage deviation from the average value was determined for each sample and each chemical element. The majority of percentage deviations are around medium values, some extend to both positive and negative spectrum. For mere purpose of illustration of data processing I introduce for instance a sample situation for three particular samples (i.e. samples with identification numbers FID 0, 71, 111) and Al concentrations and its percentage deviation of concentration. The Al concentration for FID 0 is 4.84. The average Al concentration value for all samples at Plzeň-Hradiště site is 4.165289. In round numbers, one per cent of average Al concentration at the site (given in a weight percentage of a soil sample) is then value 0.042. Speaking about sample FID 0 and Al concentration then 4.84/0.042-100 results in a percentage deviation of 15.2381% of a sample given (FID 0, Al concentration is here then 115.2381%, concerning the average values). Examining FID 71 the result evinces value of 101.6667%, almost the average value; contrary for FID 111 the result shows the negative percentage deviation of -31.1905% from the average concentration of Al.

The average concentrations and their negative or positive deviations from the mean were calculated for all of the samples and for all of the elements detected at the examined site. I created histograms for each element, displaying the curve of oscillating percentage deviations from the average concentration values, given in a mass percentage of a sample measured. A regular type of graph in integer auto mode (there is no firm number of categories given, the programme Statistica 12.5 determinates itself what number of categories is the most suitable to draw an appropriate graph) was used. The axe y describes the number of observations, which means literally the number of samples. The axe x in our case describes the percentage deviation from the average value calculated. A resulting visualization seems to divide the graphs into several groups of histograms. The first group consisted of As, Ti, Mn, Zr and Si seems to be following a similar pattern (Fig. 20). The distribution of both negative and positive percentage deviations is regularly spaced, as well as the similar number of cases around the average deviation. The second group seems to be small and the histograms indicate that there is normally a very low concentration of Cr and Mg at the site (Fig. 21), but there are some small numbers of samples with anomalously high concentrations of certain elements, especially Mg. The low concentration represented here by negative deviation might distort the histogram curve; however it shows the situation at the site. If I had used only histograms for statistical purposes, I would have used median in this case. Eventually, the histograms will be supplemented with interpolated maps of concentrations and distribution maps, thus for purposes of this study I was content with the use of arithmetic mean. The third group comprising two histograms of Ba and Ca seems to be very strong around the average value and they show only minor changes in the positive percentage deviation (Fig. 22). The fourth group of graphs consists of histograms of Al, K, Ni, Sr and Rb (Fig. 23). The members of this group show a very strong and stable situation around the medium percentage deviation; however all of them have a small number of cases with very high anomalies. These high anomalies range from 100% to 140% of positive deviation regarding the average value. Nickel is the only element that shows here in a very small number of cases the positive deviation from the average concentration value given of 300-350%. The last group of histograms involves elements of Fe, P, Zn, Cu, S, and Pb (Fig. 24). Histograms of this last group carry a similar sign of a major negative deviation from the mean, which shows the weaker concentration of described chemical elements at the site. Nonetheless, all of these elements were sometimes detected in very high concentrations, but only in a limited number of samples. Highlighting the two last groups with their high concentrations is important; the prevailing majority of chemical elements belonging to these two groups is commonly considered as important for archaeological survey (as mentioned earlier in chapter 2.1).

Chemical elements, significant for archaeology, emerge at the Plzeň-Hradiště site in various concentrations, as it was shown earlier. While working with histograms I used calculated negative or positive deviations from an average concentration value of an element given. This way of processing the data set provided enabled to assess general distribution of all chemical elements detected at the site, however without any relationship to the spatial distribution of these elements. Examining the results we can see some chemical elements of minor archaeological importance, i.e. As, Ti, Zr, Si, Ba, Cr. Working on the second stage of results, I created and examined scatterplots and hence the correlation of those elements, commonly considered as important for archaeological research. It is clear, that the concentrations of P were positively correlated with concentrations of Zn, K, Cu, Al, S, Ca. Nonetheless, almost all of the positive linear correlations of P and mentioned elements can be considered as very weak or weak ones ($r < 0.1$ for Zn, K, Cu and moreover the $p > 0.05$, which doesn´t make the correlations statistically reliable.) Positive, linear, but weak correlations of P and Al, Ca, S (Fig. 25, 26, 27) ($r > 0.2$ for Al and Ca, $r > 0.5$ for S, $p < 0.01$) can be tracked in the elements concentrations for the site. The strongest positive linear correlation was found for Zn and Cu (Fig. 28) ($r = 0.83$, $p < 0.01$). There was a high variability in Al, Ca and Si concentrations within the study area, but this variability (especially of Al and Si) was connected to the varying proximity of the local geology and existence of modern encroachments to the surface and soil forming processes rather than to ancient settlement activities. The concentration of Ca was negatively correlated with the concentration of K (Fig. 29) ($r = -0.5$, $p < 0.01$).

Maps of sample distribution and concentrations of particular elements were produced for every measured element together with interpolated maps of elemental concentrations. These maps can help us connect the information obtained by means of histograms and correlation graphs with the spatial location and visualize potential spatial patterns. I compared the interpolated maps with the sample distribution maps. The inner area of enclosed settlement lacks any higher and more significant concentrations of Mg, Mn, Ni and S (Fig. 30, 31). There are some higher concentration values of Mg and Ni at the southern part of the site, higher Mn concentration emerges at the western slope area and stronger concentration of S can be detected in the closest vicinity of the road, however in the case of S the result is probably strongly affected by the existence of a modern infrastructure, since S is often heavily contained in fuel (Bielaczyc 2002, Sher 1998). As it also has been made obvious by the means of histogram visualization, the deviation from the mean of these elements showed either rather stable, stronger concentrations having several low anomalies or generally low concentrations at the whole extent of the site with a very small amount of extraordinary cases.

There is an interesting situation concerning the existence of strong, positive linear correlation (Zn:Cu; $r = 0.83$, $p < 0.01$) between Zn and Cu (Fig. 32). The correlating circumstances can be clearly seen and displayed in the interpolated map. Several individual samples possess very strong anomalies of both elements, which are often present in plants and animal biomass. Remarkably high concentrations of both components in soils and sediments can indicate mining and metallurgical activities of nonferrous metals (Horák and Hejcman, 2016), but this is not our case. Cu and Zn are present in low concentration in biomass and organic waste, the accumulation of which on archaeological sites can be still detected after several millennia (Šmejda et al. 2017).

Comparing the interpolated maps and maps sample distribution and their concentrations we can see another group of chemical elements (Ca, Fe, Mg, Al, Ti and Ni) having similar spatial distributive features (Fig. 33, 34). As stated above, Mg and Ni seem to have stronger presence in samples at the southern and southern part of the site, where parts of massive rampart are present. However, this area is massively damaged by the only road accessing the nowadays settlement of Hradiště. The situation is likely to be similar for Ca and Fe, together with Al and Ni, although Al and Ni vary in their spatial distribution in a greater extent. Increase of Ca and Mg on archaeological sites in Central Europe is frequently associated with the usage of Ca and Mg rich clay sediments for the construction of buildings, deposition of mortar or plaster from the destruction of buildings and with the deposition of biomass ashes and bones (Hejcman et al., 2011, 2014; Salisbury, 2013; Šmejda 2017b, 155). Other elements, such as Al, Ni, Pb can concentrate in archaeological contexts connected with burning of biomass or food processing (Fleisher and Sulas 2015, 60). I examined the results of magnetometric survey performed by R. Křivánek in May and June 2013 (Fig. 35) and compared them with interpolated maps created within this study. According to R. Křivánek (2013, unpublished report) there is a prominent archaeological situation at the east-southern part of enclosed settlement detected by means of magnetometric survey. The magnetometric survey detected there an arc-shaped curve of strongly magnetic line of the vitrified rampart heading back towards the inner area of a site. The context is related to the outer fortification rampart without any doubts, however it may also mark out the possible existence of the today vanished entryway or the existence of a gate to the enclosed rampart. The gate could have been destroyed by a road construction, heading to Hradiště. We can only speculate if this significantly higher concentrations of Ca and Mg around this spot could in this context possibly denote a former existence of a construction, linked to the entrance way or gate.

The strongest concentrations of P are spatially distributed at the western and north-western side of the enclosed settlement, where the terrain goes down steeply. As presented earlier, P positively and linearly correlated with K only in a very weak manner. The highest value numbers of K are located also at the western side of the enclosed settlement, although their spatial distribution seem to reach a little bit more into the inner area of the top plateau. The high values of concentrations of Si and Mn give the impression of spatial correlation with P and K to limited extent (Fig. 36, 37). On the other hand, according to the histogram visualization the percentage deviation of concentrations of Si and Mn do appear to be quite stable at the site, thus these values are probably connected to the vicinity of the local geology, erosion and activities in the recent time. I also compared the interpolated and distribution maps created with the output of survey performed by R. Křivánek (Fig. 38) in May and July 2013. Both of the methods applied (magnetometry, electrical resistance) at the site confirmed strongly vitrified rampart and stone constructions at the western margin of the area measured. Several magnetic and resistance anomalies also emerged in the rampart proximity towards the inner area of the enclosed settlement. Activities connected with fire wood or wood coal burning and consequently with the production of ashes and organic wastes whose deposition noticeably increases P, K, and also Ca, Mg, Cu and Zn concentrations in the soil were described by several authors (i.e. Hejcman et al. 2011; 2013). Possible existence of a wooden construction within the rampart could be a relatable explanation of high concentration values of P and K at the western sideline of the site. According to L. Šmejda (2014, 248) and the results of a spatially limited XRF research from 2013 of the vitrified rampart section in the northern site area, the stratigraphic units at Plzeň-Hradiště which are expected to have high organic content like remains of wooden constructions or dark cultural layers show enrichment in C, Ca, P, Sr, and Zn, whilst samples of the bedrock unaffected by human activities are lacking increased levels of these elements and instead they are much stronger in K, Na, Ni, and Si.

Very clear spatial distribution of the strongest concentrations is visible among the group of Al, As, Ba, Cr, Pb, Sr, Rb, Zr (Fig. 39, 40, 41, 42). The absolute highest values of all of listed chemical elements undoubtedly cover the extent of the then sand quarry (a large sandpit damaged at least 20% of the inner area of the enclosed settlement), that is at the present time eventually recultivated. According to the results of magnetometric survey (Křivánek 2013, unpublished report), this sand quarry was probably brought to even greater extent especially to the northern direction, than it is visible in the aerial picture originating in 1957, causing irretrievable damage over 30% of the archaeological heritage (Fig. 43). The compact extent of the sand quarry is in the outcomes of the magnetometric survey clearly visible, substantially marked by a magnetic inhomogeneous and numerous metals contaminated area.

4.5 Discussion

The first message of the later part of this study is that large-scale elemental composition mapping of the present-day topsoil stratums by means of pXRF can be employed for a rapid and cost-effective survey of the variations in local geology and soil forming processes. Large-scale mapping of chemical elements concentrations has a huge potential and can be indicative of both ancient settlement activities and recent human impacts.

The most useful elements for the detection of ancient settlement activities at the site seem to be P, K, Zn, Cu. Although the most frequently analyzed element in archaeological soils and sediments is P, the anomaly concentrations of other elements (as described in the chapter 2.1 within this study) enable to help to bring to light the pattern discovered by the P analysis. There was a strong concentration of S detected. The accumulation of S is connected with the decomposition and deposition of organic material and S plays an important role in the organism of plants and animals (see more in the chapter 2.1). Despite of increased concentrations of S at the great extent of the site the values were not much useful. Cycling of S in ecosystems is much faster than cycling of P and that is why extraordinary increased S concentrations in soils and sediment are indicative of their recent origin. It is possible to use the knowledge of the differential cycling rates of P and S as a proxy for the differentiation between the recent deposition of organic P and its ancient accumulation (Šmejda et al. 2017, 63). The significantly increased levels of concentrations of K and Si revealed within this study compared with results from the vitrified rampart section by L. Šmejda (2014, 248); especially in the proximity of the western slopes of the site also could possibly be a sign of the erosion process, bringing the bedrock layers unaffected by human settlement activities closer to the surface.

High concentrations of Ca, Fe and Mg were detected at the southern part of the site. Although these elements carry an importance for the archaeological investigation, there should be performed more detailed excavations and pedological and geological research to evaluate the situation at the site in this area and the relations to concentrations of Ca, Fe and Mg and to any traces of ancient settlement activities. There was no measurable increase of Ca within the enclosed settlement, even though settlement activities are commonly connected with Ca increase due to the deposition of biomass, ashes and mortar. At the site there was detected Ca-rich metabasalt material. In the rock it could be expected the presence of other minerals of sanidinite facies mostly of Ca-Si-Mg-Fe system (Zavřel in Šmejda 2013, 187; unpublished report). The absence of the higher Ca concentrations could be explained by the presence of Ca-rich material, which masks the human-induced deposition of Ca. Several authors have stated that high Ca accumulation in prehistoric settlements is easily visible especially in Ca-poor acid soils (Šmejda et al. 2017, 70). At the site, Ca concentrations were particularly low within the middle site area, probably as the result of process, where Ca has been leached away over the centuries of soil development. Ca concentrations were higher on the steep western slopes and at the southern area of the site. On the western slopes it is probably the result of erosion, which brings to the surface younger soils layers, from which Ca has not been leached yet. The higher concentrations of Ca, Mg and Fe on the southern part of the site, disrupted by the recent encroachments of a road construction and power voltage lines construction, could be given by the bedrock basis, brought to the surface due to recent interventions. On the other hand, the magnetometric survey stated at the spot some magnetic anomalies admitting the existence of an entryway, which could be related to the higher concentrations of mentioned elements. Complex cross-discipline survey in the future is required to shed the light to this specific space.

Concentrations of Zn and Cu showed the greatest concordance regarding the spatial distributions as well as positive linear correlation. Zn and Cu are microelements present in some quantities in plant and animal biomass and their enlarged concentrations have also been considered as indicators of human activity (Oonk et al., 2009). As stated earlier, the enlarged concentrations marking the polluted environment could reflect the former metallurgical or mining activities of nonferrous metals (for more information to this topic see Ash et al. 2014; Horák and Hejcman 2016). One of the spots with the extraordinary high concentration of both elements, however, is located in the space of the recultivated sand quarry, which excludes it out of having a massive archaeological importance. The second area rich in Zn and Cu is located in the close proximity of the northern vitrified rampart and nowadays road. The vicinity of the modern infrastructure might have an impact and be reflected in the enlarged values of concentrations and so in the polluted soils. The extent of the area close to the northern vitrified rampart is worth of more detailed future survey to enlighten the conditions of this site´s part.

Assessing the interpolated and distribution maps created, together with results of XRF analysis displayed in scatterplot graphs and histograms, results of magnetometric and electrical resistivity surveys it is possible to claim, that Plzeň-Hradiště site has been clearly and significantly destroyed over the course of time. The largest damage regarding the archaeological heritage was perpetrated by making use of a site part as a sand quarry. The damage is visible in its whole extent because of clear spatial distribution of stronger concentrations of Al, As, Ba, Cr, Pb, Sr, Rb, Zr. Most of these elements belong to the group of risk elements, the increased concentrations of which are dangerous for human health and environs. Majority of them enter the natural environment because of combustion of fossil fuels, deposition of waste, use of other propellants, mining activities and use of artificial fertilizers, herbicides etc. (Petr 2016). I work on the assumption that these high concentrations of heavy metals and other rather toxic elements were contained in the backfill material that was brought to the area of the former sand quarry while recultivation. The provenance of the backfill material remains unknown. De Silva et al. (2016) mentioned several sources of environment pollution by heavy metals because of transportation vehicles. Propellants (containing As, Cr, Cd, Hg, Mn, Ni, Pb, Se and Zn), engine oils (Cd, Cr, Ni, Zn, W), wearing out of tires (Cd, Co, Cu, Cr, Pb, Ni, Se, Zn), wearing out of brakes (Ag, As, Cd, Cu, Cr, Ni, Pb, Sb and Zn), exhaust catalytic converter (Pt, Pd, Rh) could all to contribute to the environmental pollution. However in this case we assume that the contamination, caused by transportation vehicles and various industrial machines used while sand mining is only the secondary cause. The concentration values were measured at the contemporary surface and most probably have a little relation to the then sand extraction.

While these chemical elements themselves have nothing much to say to the archaeological investigation regarding the ancient settlement activities, there is a vast potential in detecting of these and other toxic chemical elements in preliminary archaeological investigation. It is possible to roughly estimate the spatial expanse of space afflicted by modern interventions and recultivations by assessing areas evincing out of usual high concentrations of toxic elements. Such a preliminary survey could not merely determine the subsequent course of an archaeological research, but it could help to clarify state of the archaeological site from the point of view of the protection of the historic monuments and protected spaces. A survey of this nature would be able to cast light to the past encroachments. Based on its results it shall encourage best practices regarding the protection of cultural heritage sites and historical monuments, including the awareness of the local public and counselling on the protection of the historic monuments and protected spaces and on the legislation and implementation of measures related to heritage, together with collaboration on professional training.

Within the recent field project at Plzeň-Hradiště a grain size analysis was performed by Doc. Lenka Lisá, PhDr; however only in a considerably spatially limited extent. It has been noted in geological materials that variation in grain size can have differing effects on the intensities of different elements (metals especially) within the same sample. It is important to ensure uniformity in grain size since dissimilarity will mean differential penetration of the X-rays into the sample. In general, the smaller the grain size, the greater the penetration of the X-rays and the more fluorescence counts are recorded (Scott et al. 2016; Ogburn et al. 2013). Scott et al. (2016) and the team examining the Roman iron industry in Sagalassos, Turkey, wrapped the samples in plastic, placed on a metal plate, and struck with a hammer. The collected powder was then sieved through a fine mesh to ensure that the samples had as homogeneous a grain size as possible and then performed various quantitative chemical analysis. It is important to ensure uniformity in grain size. The importance of a grain size effect regarding the pXRF measurements specifically in archaeological research has not been broadly recorded and described yet. However, grain size effect is a commonly known problematic in other fields, such as research of sediments of lakes and rivers. Horowitz and Elrick (1988) noted that one of the most significant factors controlling bed-sediment capacity for collecting and concentrating trace metals is grain size – as grain size decreases, metal concentrations increases (Horowitz and Elrick 1988; Prohič and Juračič 1989). Commonly, the grain size effect is minimized by either mathematical normalization of bulk chemical based upon an independent grain size analysis, or physical separation of a size range or fraction followed by a chemical analysis of a separated material. The data show that strongest correlations between metals occur with the percent <63µm grain size fraction (Horowitz and Elrick 1988; Förstner and Salomons 1980). The fraction <63µm is recommended for the following reasons: Trace metals have been found to be present mainly in clay-silt particles. This fraction is nearly equivalent to the material carried in suspension (the most important mode of sediments by far). Also, sieving does not alter metal concentrations when water of the same system is used (here we speak about research of bed sediments of rivers and lakes) (Förstner 1990, 405). Similar conclusions and knowledge about the grain size effect should be assessed and applied to archaeology in a broader extent, especially regarding the chemical analysis of trace elements in anthropologically altered soils and sediments.

5. Conclusion

Aiming to establish and broaden the general knowledge of chemical and physical properties of soils and sediments concerning the archaeological investigation within the thesis I introduced a broader approach of geochemistry and geophysics in the archaeological field. I described generally numerous geoarchaeological methods. Detailed information about the archaeological research at Plzeň-Hradiště in 2012 and 2013 and its results is involved. Within the study I examined by various means provided XRF data from Plzeň-Hradiště.

In order to answer the first and the second question asked in the introduction of this study (Can the large-scale mapping of the elemental composition of the upper layer of contemporary soil be used for the detection of ancient settlement activities at Plzeň-Hradiště? Which elements, in addition to P, indicate ancient settlement activities and seem to be the most useful in the conditions of this particular site?) I arrived to the conclusion that detected elements do create meaningful patterns and especially the increased levels of of P, K, Zn and Cu in the contemporary topsoil layer covering the site Plzeň-Hradiště seem to bear an archaeological importance. Increased concentrations of P and K correspond with the results of magnetometric survey performed by R. Křivánek and detect the vitrified rampart on the western sideline of the site. An extraordinary strong positive linear correlation (Zn:Cu; $r = 0.83$, $p < 0.01$) has been detected. However, this regards only several spots at the site and one of them is located within the area destroyed by the then sand quarry, which excludes it from having a greater archaeological value. The second spot is located at the northern side of the site and demands further examination to reveal its relationship with ancient settlement activities. Increased levels of Fe, Ca and Mg were measured at the southern part of the site, corresponding with results of magnetometric research indicating a prominent archaeological situation; complex cross-discipline investigation in the future is essential in order to shed the light to this specific space.

With the intention of answering the third question asked in the introduction (How much is the concentration of different elements affected by recent and modern interventions to the extent of Plzeň-Hradiště site? Could a geoarchaeological preliminary survey determine the subsequent course of an archaeological research and help to clarify state of the archaeological site from the point of view of the protection of the historic monuments and protected spaces?) I can reach to the general consensus regarding the area of the then sand quarry, which is nowadays not visible at the current surface. Nonetheless, this area is undoubtedly visible in the chemical data display and is resembled by results of magnetometric research as well. Especially increased concentrations of Al, As, Ba, Cr, Pb, Sr, Rb, Zr evince clearly this particular space damaged for archaeological purposes. Using pXRF, large-scale mapping of the elemental composition of the topsoil layer on archaeological sites can help to identify the extent and type of ancient settlement activities and determine the following stages of archaeological research. This research suggests that archaeological sites symbolize not only an important segment of cultural heritage, but that they also play a noteworthy, though under-studied, role in the long-term protection of the historic monuments and protected spaces.

Large-scale mapping of the elemental composition assessing the damages at the archaeological sites made by recent interventions could improve the protection of similar sites and monuments in the future, including increasing of awareness of the local public and counselling on the protection of the historic monuments and protected spaces and on the legislation and implementation of measures related to heritage

6. Shrnutí

Předložená diplomová práce se ve své první části zabývá širším shrnutím a představením metod geochemie a geofyziky aplikovaných v rámci archeologie. Zmíněné metody jsou v práci popsány a diskutovány v souvislosti s chemickými a fyzikálními vlastnostmi sedimentů a půd v archeologickém výzkumu. V současné době je známo, že lidská minulá i současná aktivita má na chemické a fyzikální složení půd a sedimentů velký vliv. Změny v půdním složení mohou být měřeny a analyzovány mnoha různými způsoby. Archeologie si opakovaně klade otázky ohledně formačního procesu archeologické lokality, stability osídlení, využití sídlištního areálu, typu převažující ekonomiky a způsobu sociální organizace, co se areálů aktivit týče. Výsledky geoarcheologického výzkumu mohou minimálně indikovat mnohé odpovědi na kladené otázky. Geochemické a geofyzikální průzkumy často nabízejí výsledky, které nemohou být plně spojeny s prehistorickou sídlištní aktivitou. V úvahu musí být brána také geologická a geomorfologické situace v oblasti dané archeologické lokality a půdní formační procesy. S nutnou dávkou opatrnosti mohou být výsledky geoarcheologického průzkumu interpretovány pomocí různých statistických nástrojů a vizuálního prostorového zobrazení. Výsledky statistických analýz a prostorových vizualizací mohou podstatně přispět k osvětlení archeologických situací.

V předložené práci jsou detailně diskutovány chemické aspekty půdního a sedimentového složení v souvislosti s archeologickým výzkumem. V kapitole 2.1 „Geochemistry in archaeology“ jsou popsány jednotlivé chemické prvky, které jsou při zvýšené koncentraci v půdě možným indikátorem minulých lidských aktivit. Nemalý prostor je v práci dále věnován představení a popsání běžných geochemických metod, které se v rámci archeologie používají. Jmenovitě jde o fosfátovou analýzu, analýzu pH, rentgenovou fluorescenční analýzu a analýzu velikosti částic. Pozornost byla věnována i geofyzikálním metodám, které se dnes v archeologii používají. Je třeba zdůraznit, že pro archeologické lokality je nemožné použít jedinou samotnou geofyzikální či geochemickou metodu, vždy se musí jednat spíše o kombinaci několika vhodných metod. Geofyzikálních metod, které lze aplikovat pro potřeby archeologie je velké množství. V kapitole 2.2 „Geophysics in archaeology“ je popsána širší úloha geofyziky v archeologie a nástin rozličných metod tohoto odvětví. Následuje užší výběr známějších geofyzikálních metod, a to: Elektromagnetický průzkum, magnetometrický průzkum, georadar, elektrické odporové metody a metody seismické.

Druhá část diplomové práce je věnována detailnímu popisu posledního archeologického výzkumu lokality v Plzni-Hradišti, který probíhal v letech 2012 a 2013. Pozornost byla zaměřena na umístění lokality, přírodním podmínkám, historii archeologického bádání, průběhu posledního archeologického výzkumu a výsledkům jednotlivých sezón s důrazem na nedestruktivní prospekci.

V rámci své práce jsem se věnovala dále detailnímu popisu nedestruktivních geochemických a geofyzikálních metod použitých při archeologickém výzkumu v Plzni-Hradišti, které byly v předchozích oddílech spíše obecně nastíněny. Metody jsem rozdělila v práci pro přehlednější orientaci do dvou skupin. První skupina metod byla použita pro získání výsledků z řezu valem, druhá skupina metod analyzovala celou plochu dané lokality. V praktické části své práce jsem zpracovala data XRF analýzy, která byla provedena v roce 2015 L. Šmejdou na celé ploše zkoumané lokality. Výsledky praktické části měly odpovědět na následující otázky: 1) Je možné, aby plošné mapování kompozice chemických prvků ve svrchní vrstvě půdního pokryvu a jeho výsledky byly použity pro detekci minulých lidských aktivit na lokalitě Plzeň-Hradiště? 2) Které chemické prvky, krom fosforu, se zdají být v konkrétních podmínkách této lokality archeologicky nejpřínosnější? 3) Jak je ovlivněno chemické složení půdy na této lokalitě nedávnými nebo současnými zásahy? Může geoarcheologický předstihový výzkum lokalit obecně předurčit následné směřování širšího archeologického výzkumu? Může takový výzkum objasnit stav archeologické památky a nedávných zásahů z pohledu památkové péče a pomoci podobným zásahům v budoucnu předejít? Data XRF analýzy byla zpracována jak statisticky v programu Statistica 12.5, tak vizuálně zobrazena pomocí softwaru ArcMap verze 10.1 od firmy Esri. Ve všech 120 vzorcích byly měřeny koncentrace prvků Mg, Al, Si, P, S, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, As, Rb, Zr, Sr, Ba a Pb. Podrobný popis zkoumání dat a výsledky jsou obsaženy v kapitolách 4.3 „Data analysis“ a 4.4 „Results“. Kapitola 4.5 „Discussion“ obsahuje další rozbor dosažených výsledků.

V odpovědi na kladené otázky lze stručně říci, že plošné mapování kompozice chemických prvků na lokalitě Plzeň-Hradiště ve svrchní vrstvě půdního pokryvu zcela jistě přináší smysluplné výsledky, které se shodovaly s výsledky geofyzikálních měření, která byla provedena R. Křivánkem. Prvky P, K, Zn, Cu se zdají být pro danou archeologickou

informačně nejpřínosnější, co se týče minulých lidských aktivit, ačkoliv jistý potenciál zejména v jižní části lokality vykazují i prvky Mg, Fe a Ca. Nejvýrazněji se ale na lokalitě projevují právě nedávné zásahy, zde se jedná o rekultivaci pískovny. Pískovna byla zřejmě zasypána půdou, která je hojně kontaminována rozličnými těžkými kovy a dalšími toxickými prvky (Al, As, Ba, Cr, Cu, Pb, Sr, Rb, Zr, Zn). Prostorová distribuce zvýšených koncentrací těchto prvků je na výstupech vytvořených pomocí softwaru ArcMap 10.1 velice jasně vidět. Tato rozeznaná distribuce jasně kopíruje tehdejší rozsah pískovny, výsledky se opět shodují i s výsledky magnetometrického průzkumu provedeným R. Křivánkem. Právě provoz pískovny a její následná rekultivace poškodily minimálně 20% rozsahu archeologické lokality.
Lze konstatovat, že mapování kompozice koncentrací chemických prvků na archeologických lokalitách vykazuje vysoký potenciál a mělo by být součástí předstihových výzkumů, neboť může efektivně určit směřování dalších fází následného bádání a úspěšně nasměrovat například umístění sond v rámci destruktivního výzkumu. Skupiny nejvýznačnějších prvků, které detekují minulé lidské aktivity na archeologických lokalitách, se mohou v závislosti na geologii a geomorfologii na konkrétních lokalitách lišit. Zkoumané archeologické památky symbolizují nejen důležitou součást kulturního dědictví, ale detekce a výzkum škod napáchaných nedávnými zásahy hraje současně roli v i v dalším vývoji památkové péče a v budoucí ochraně archeologických památek.

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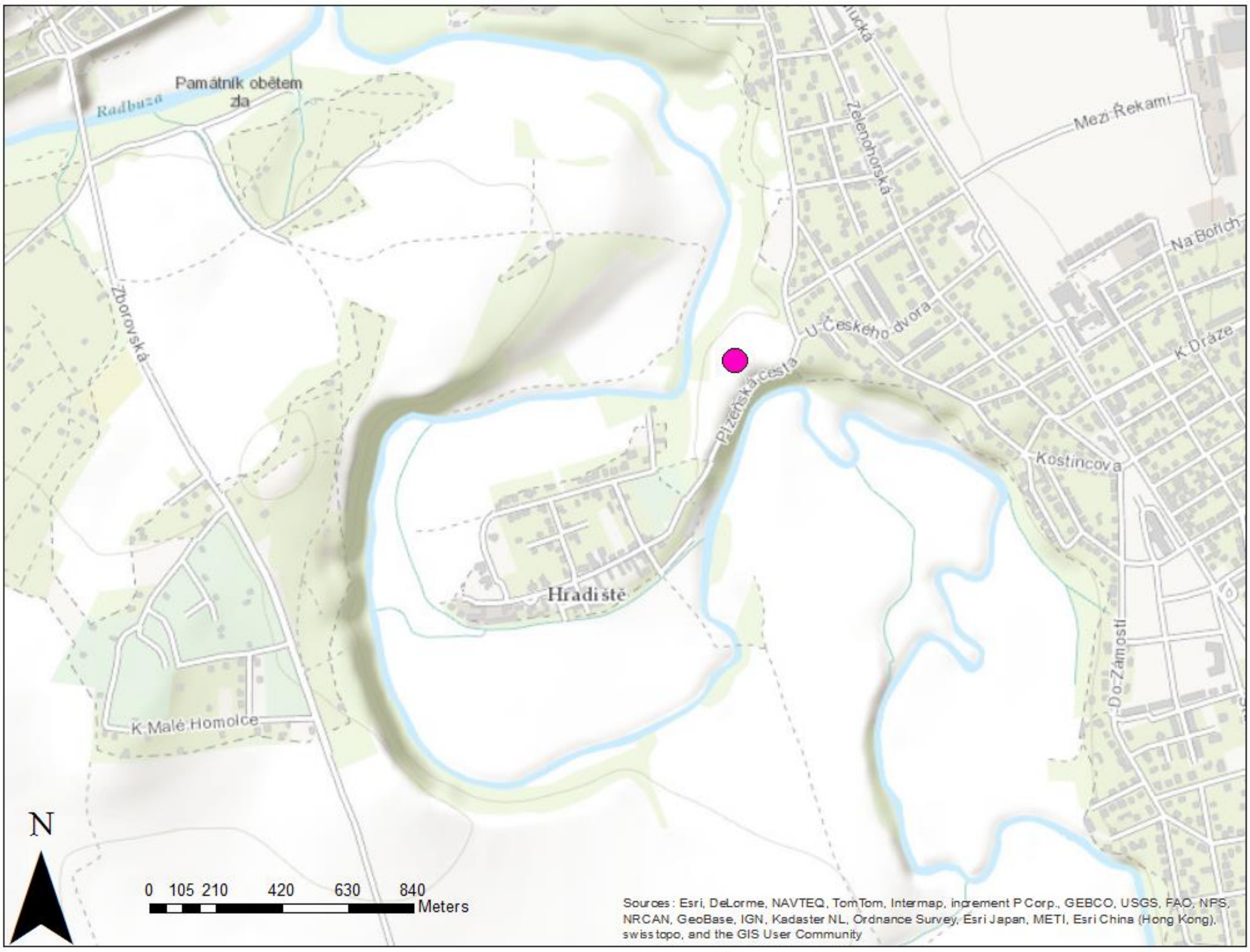
8. Figures

Fig. 1: Topographic map showing the localization of the site (Adapted in ArcGIS by the author).



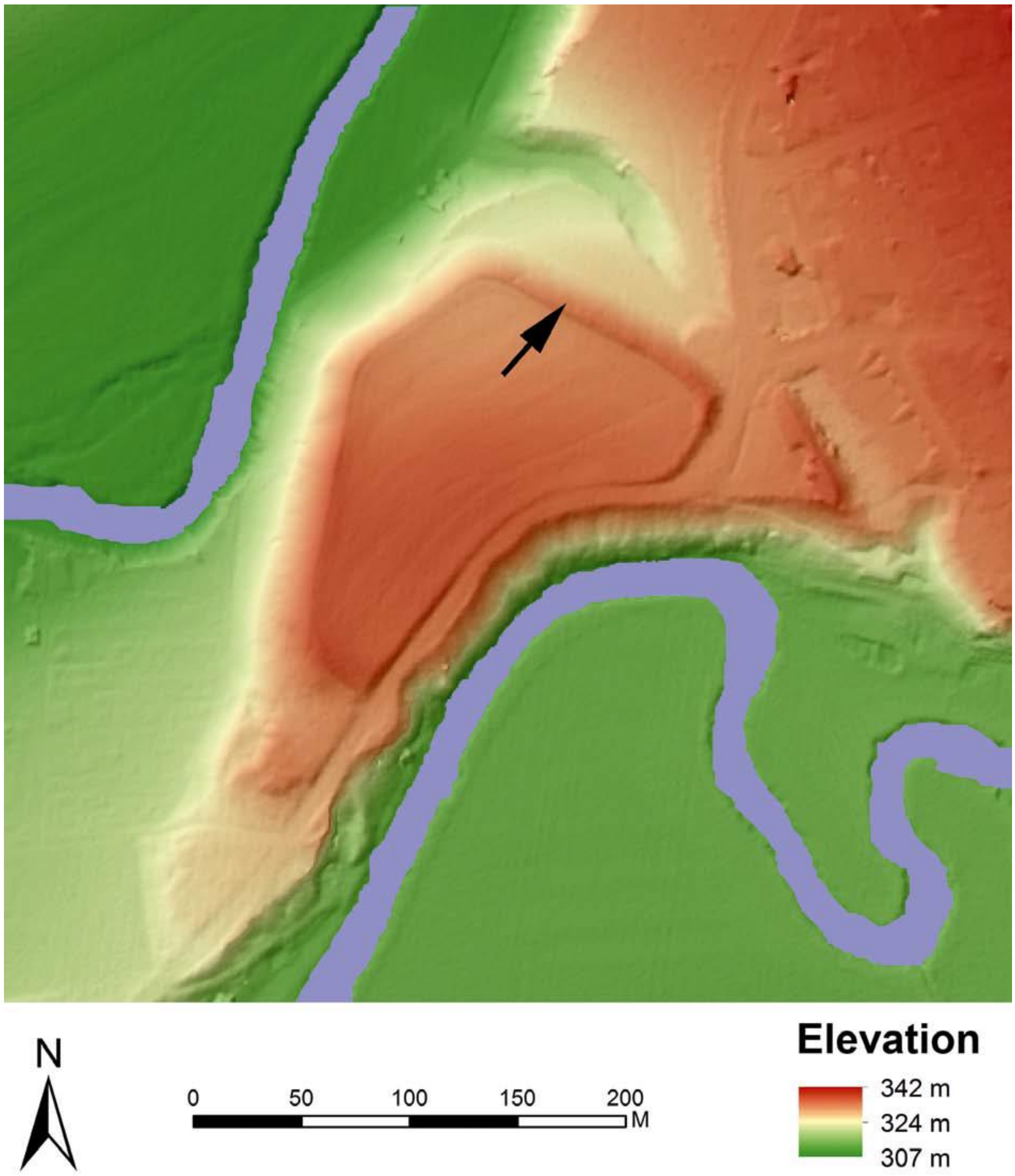


Fig. 2: Digital terrain model of the site, based on LIDAR data from the State Administration of Land Surveying and Cadastre. The eastern rampart segment detached from the main part of the site is clearly visible. Arrow marks the position of the main trench excavated in 2012–2013 (Graphics by L. Šmejda 2014, 243).

Fig. 3: Aerial winter photograph showing the hillfort (looking north). South-oriented slopes of rampart are clearly defined as snow melted there due to more intensive sun irradiation. Notice the eastern rampart segment in house gardens across the road on the right (Photo by L. Šmejda 2014, 242).

Fig. 4: A section of an aerial photo from 1956, displaying the area damaged by sand quarry (VHGMÚ Dobruška).

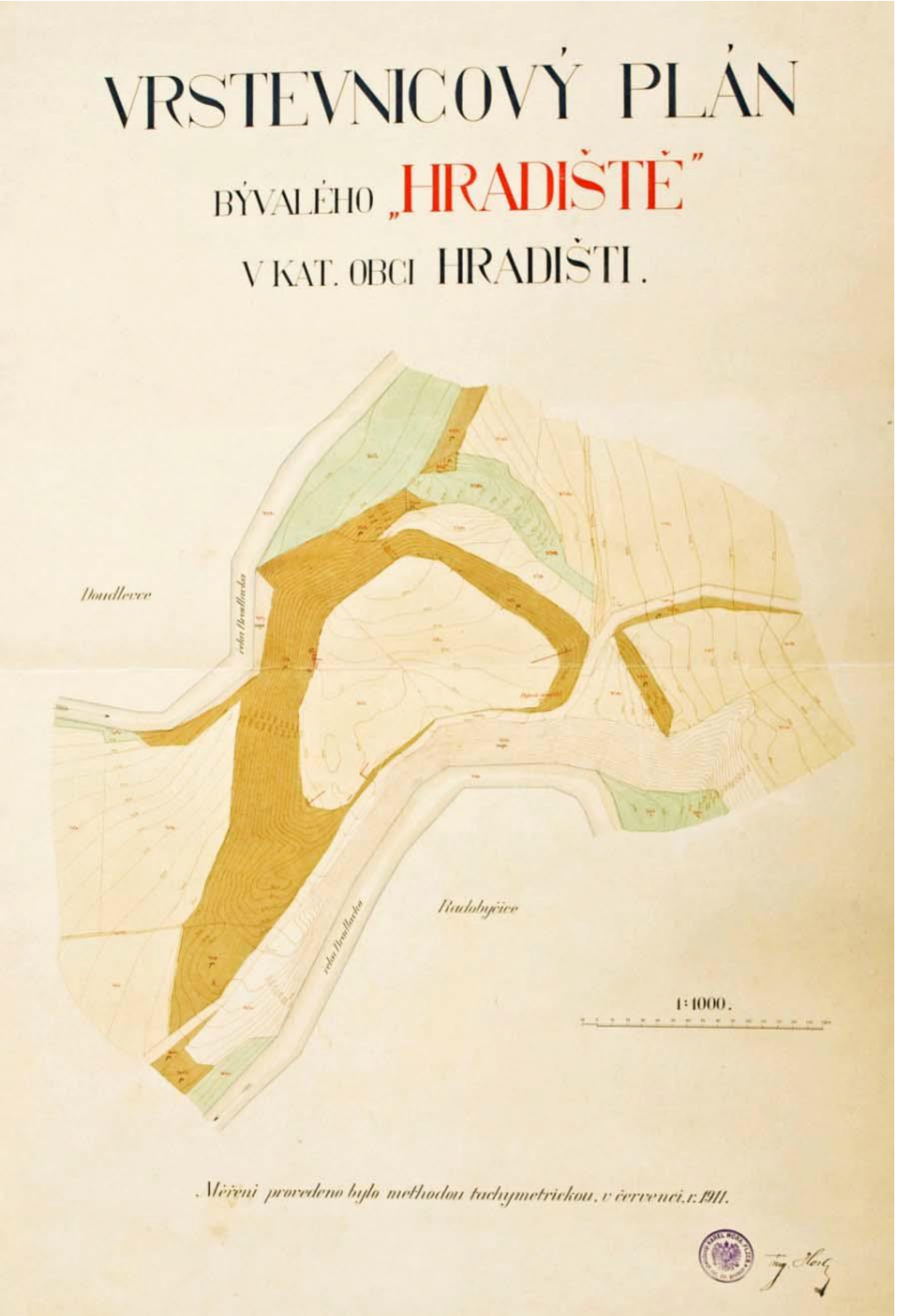


Fig. 5: The first detailed plan by F. B. Horák from 1911. The plan is archived at the Department of Prehistory of the Museum of West Bohemia, Pilsen (Šmejda et al. 2013, 14).

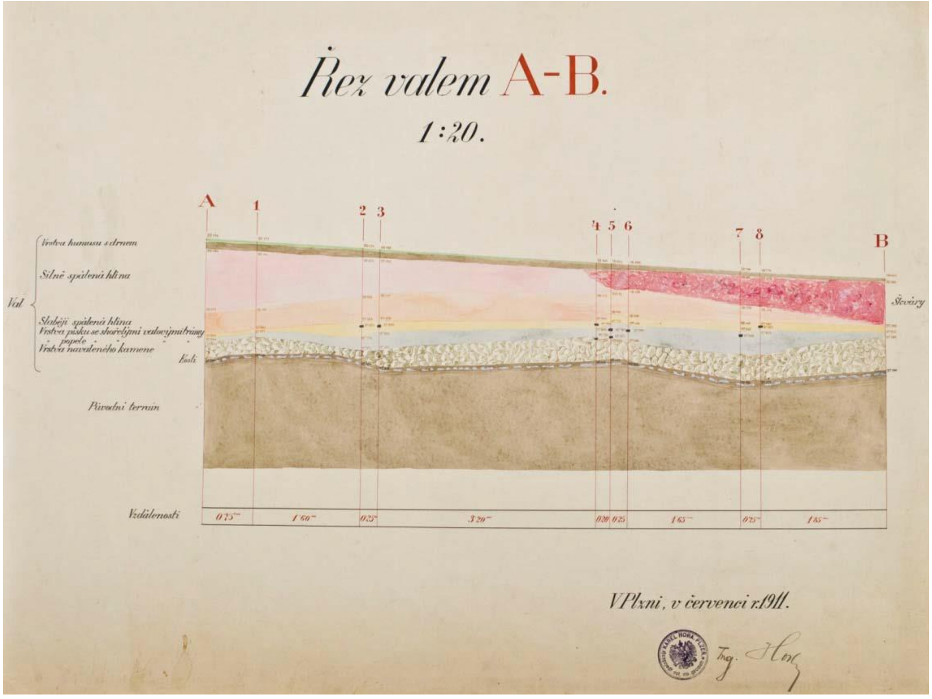


Fig. 6: A drawing of one trench section by F. B. Horák, the excavation took place in 1911. This drawing is archived at the Department of Prehistory of the Museum of West Bohemia (Šmejda et al. 2013, 15).

Fig. 7: A location of section, excavated in 2013 (Šmejda et al. 2014, 20).

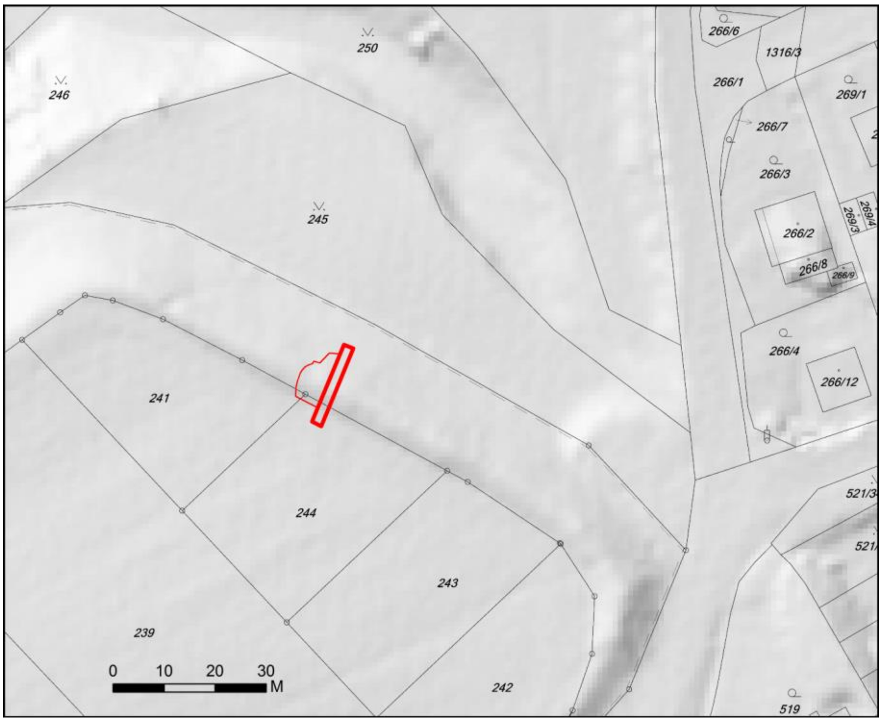


Fig. 8: Photograph of excavation of the northern rampart, end of summer 2012 (Photo by L. Šmejda 2014, 243).

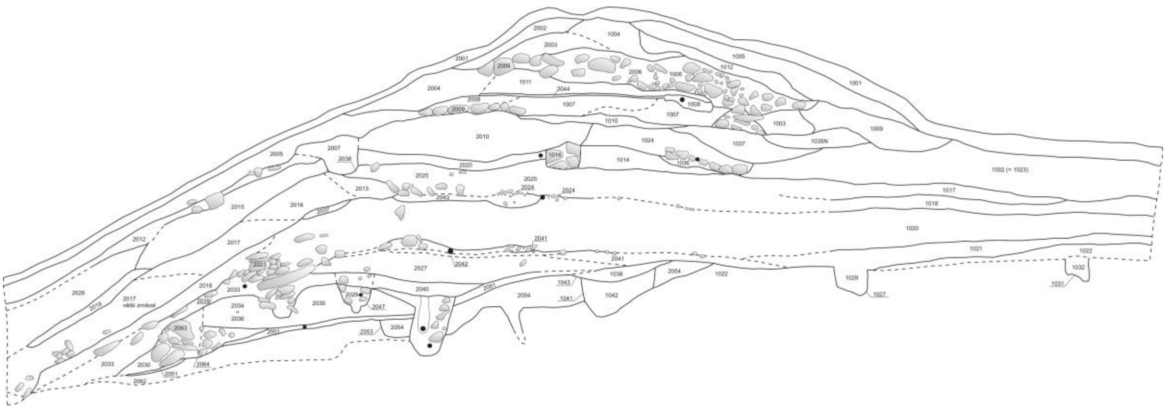


Fig. 9: Main cross-section of the northern rampart, facing east, seasons 2012-2013 (Drawing by D. Vokounová Franzeová on the basis of field documentation, provided to me by L. Šmejda).

Fig. 10, 11: A bronze ring/circle, middle Bronze Age (Šmejda et al., 56).

Fig. 12, 13: A globular pin with perforated head (Šmejda et al. 2013, 57).

Fig. 14, 15: A fragment of a bronze spiral; drawings of the bronze findings (Šmejda et al. 2013, 58).

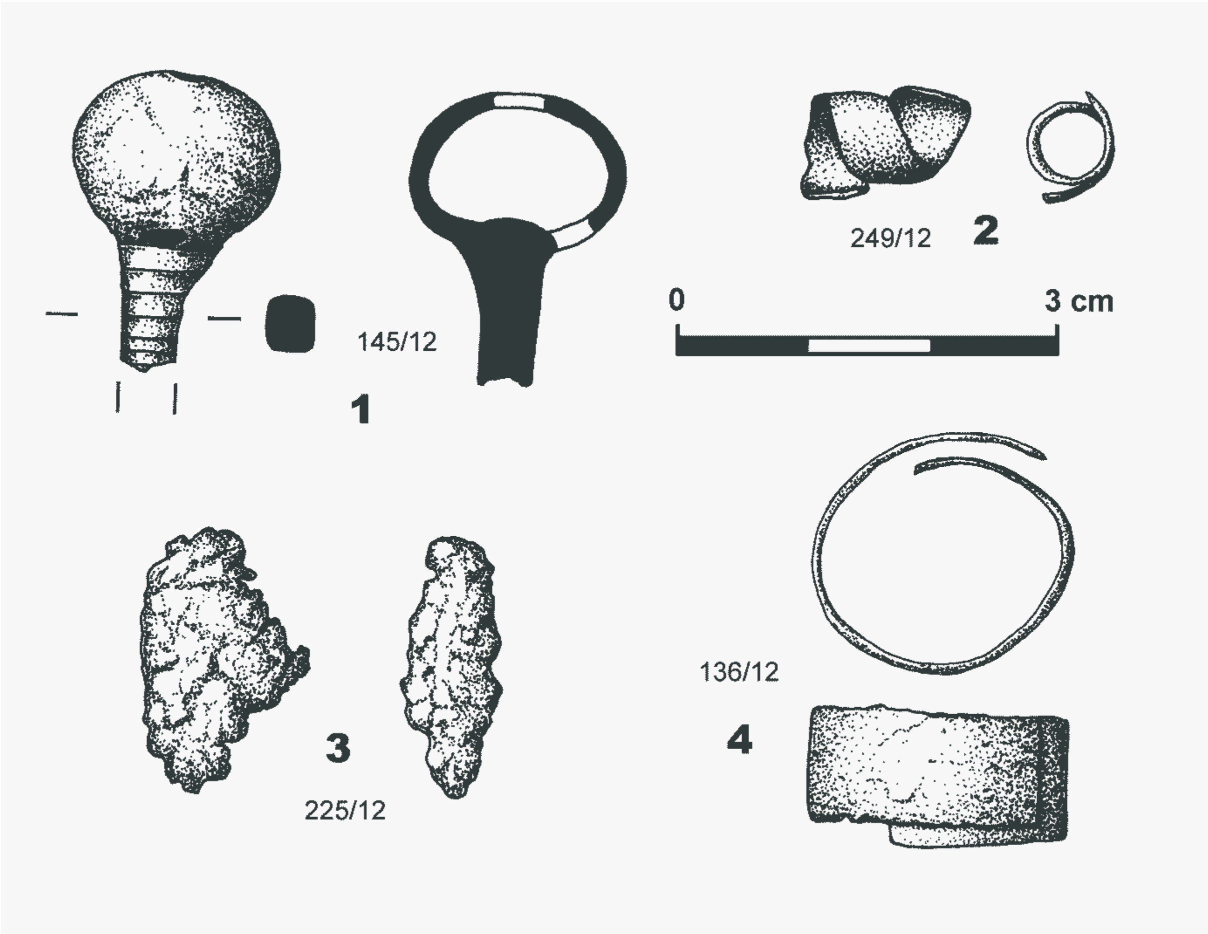
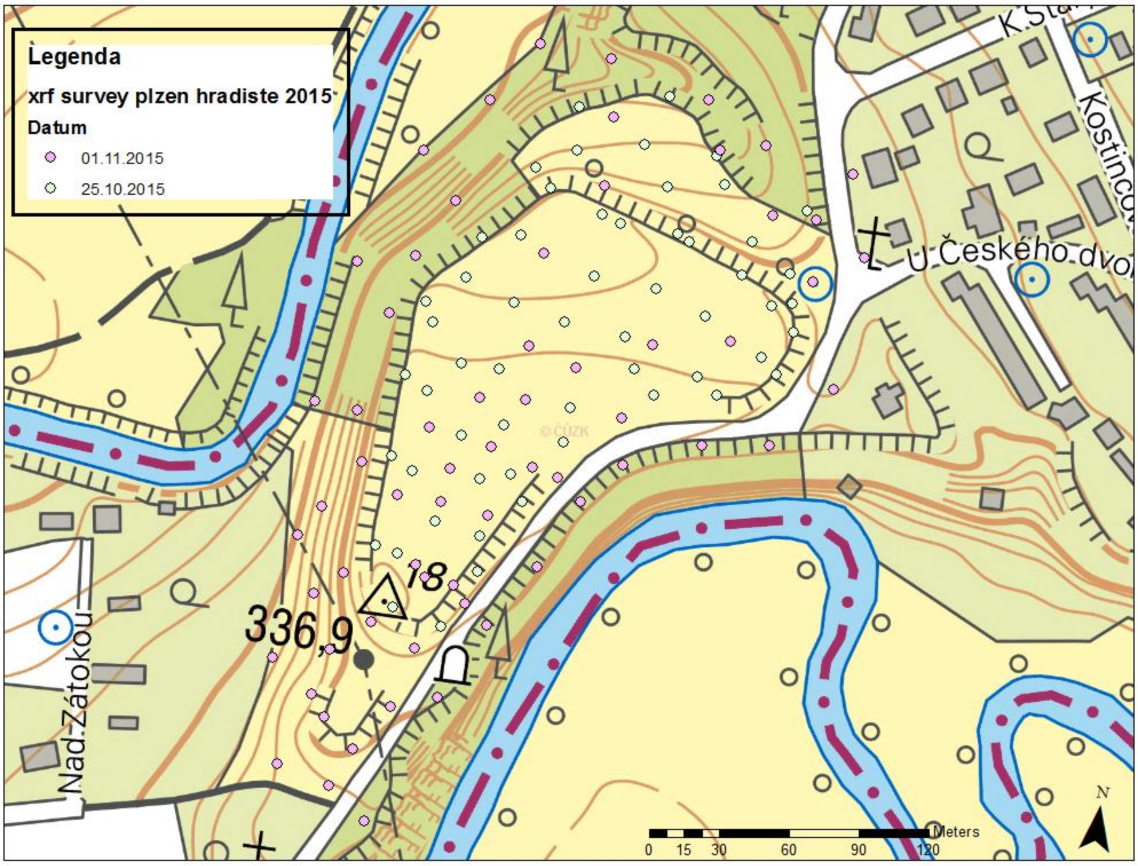


Fig. 14, 15: A fragment of a bronze spiral; drawings of the bronze findings (Šmejda et al. 2013, 58).



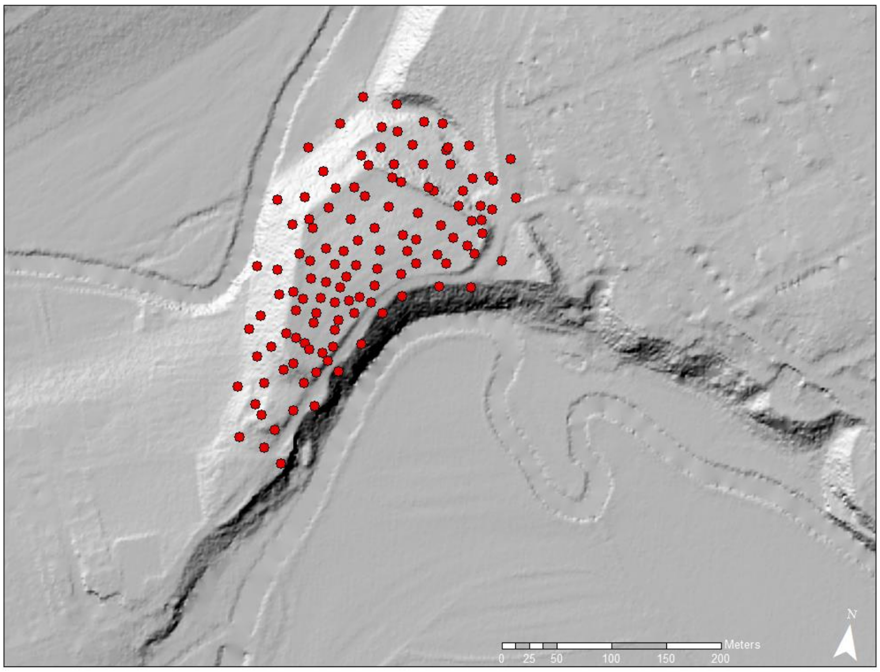


Fig. 16, 17: Spatial distribution of XRF data collection, performed by L. Šmejda in 2015 (graphics by the author Jana Spěváčková).

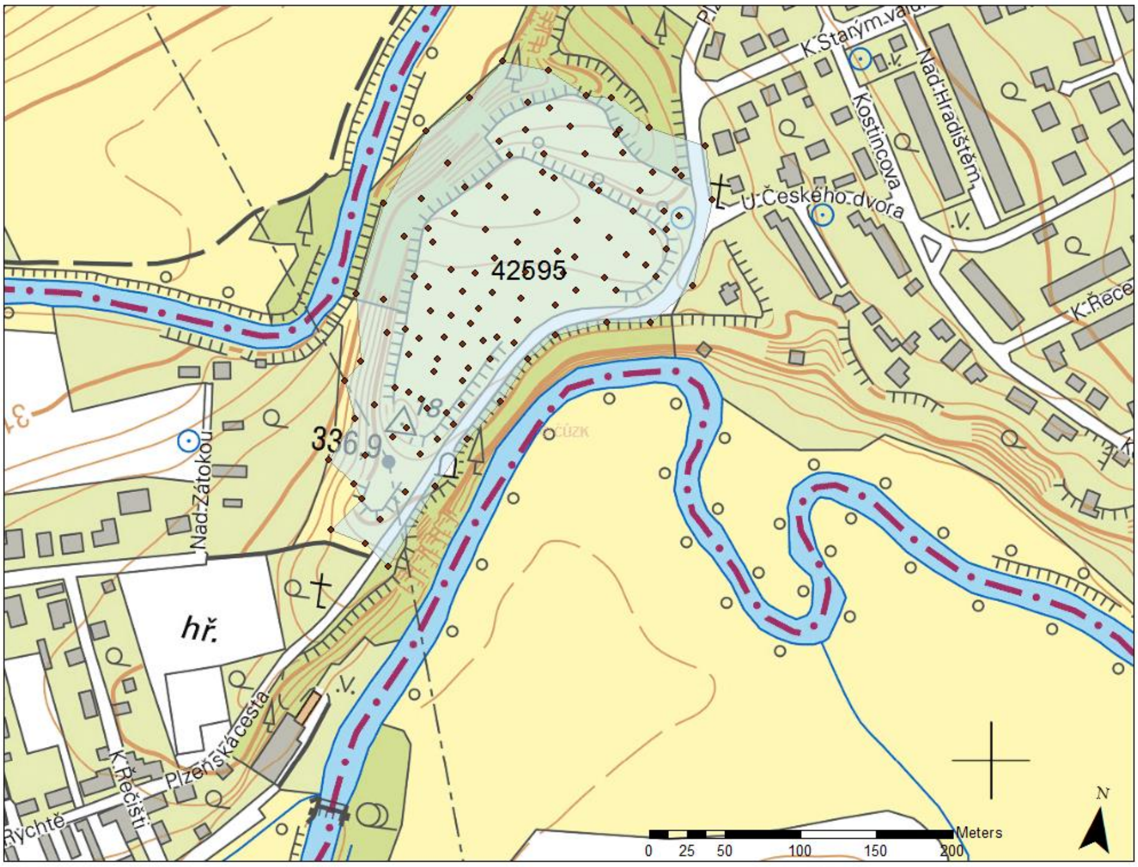


Fig. 18: The pXRF survey covered an area of 42.5 ha (polygon area calculated in ArcMap 10.1 by "Calculate geometry" command) (graphics by Jana Spěváčková).

Fig. 19: Orthophoto of Plzeň-Hradiště (ČÚZK) (graphics by the author).

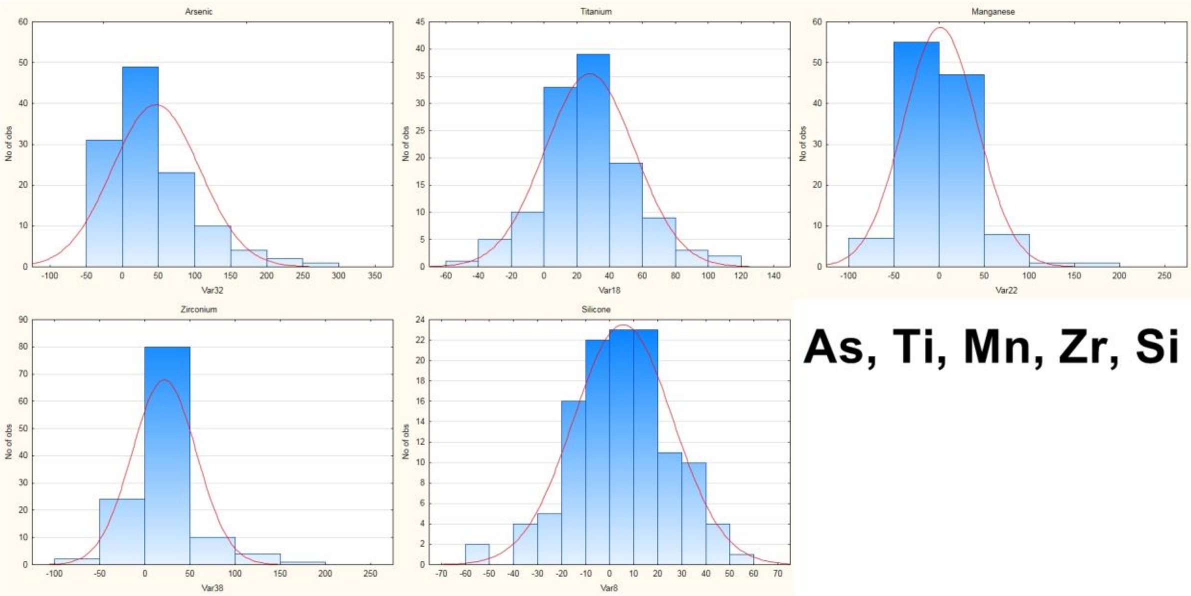


Fig. 20: Histogram of As, Ti, Mn, Zr, Si, all of the elements follow quite a similar pattern (created by the author).

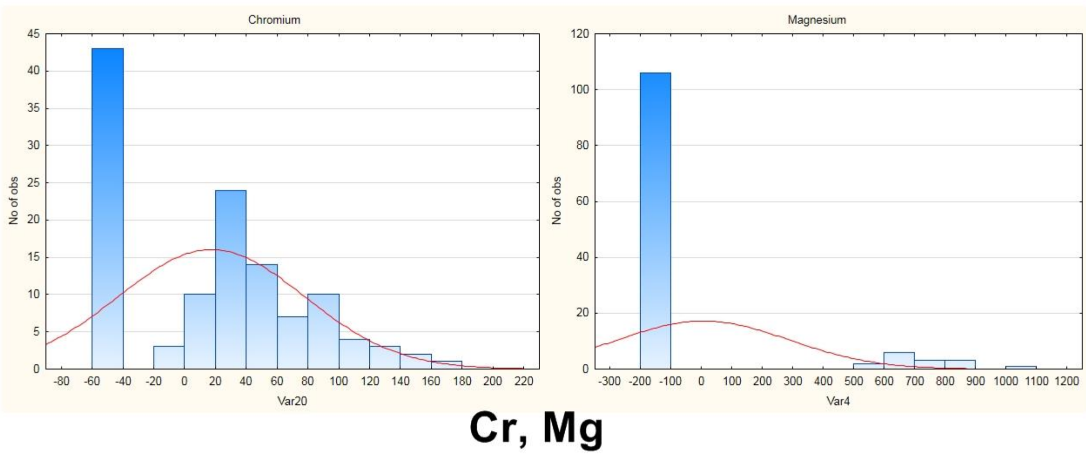


Fig. 21: Histogram of Cr and Mg, showing small numbers of samples with anomaly high concentrations (created by the author).

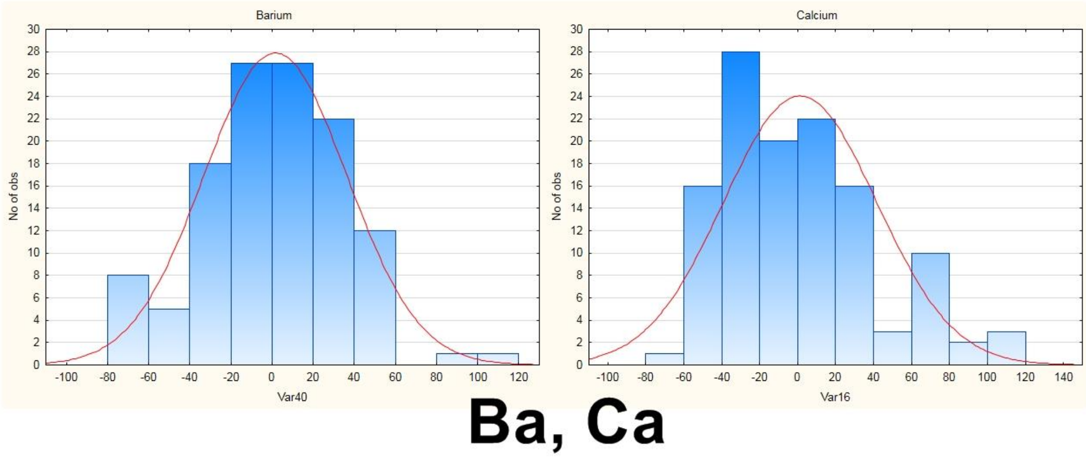


Fig. 22: Histogram of Ba and Ca, both of elements seem to bevery strong around the average value and they show only minor changes in the positive percentage deviation (created by the author).

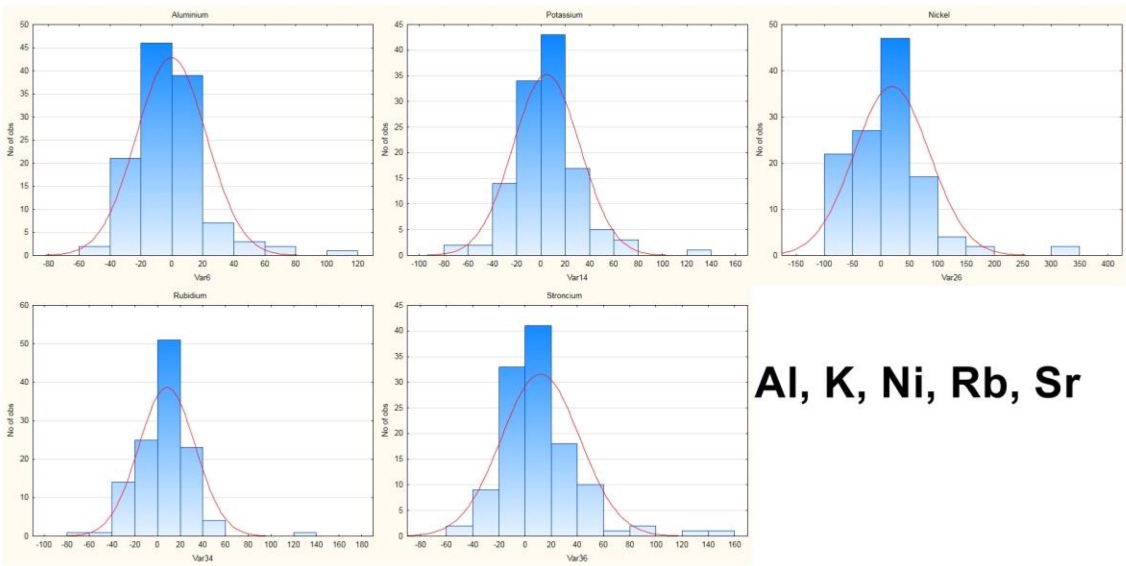


Fig. 23: Histogram of Al, K, Ni, Rb and Sr. These chemical elements seem to possess very strong and stable situation around the medium percentage deviation; however all of them have a small number of cases with very high anomalies (created by the author).

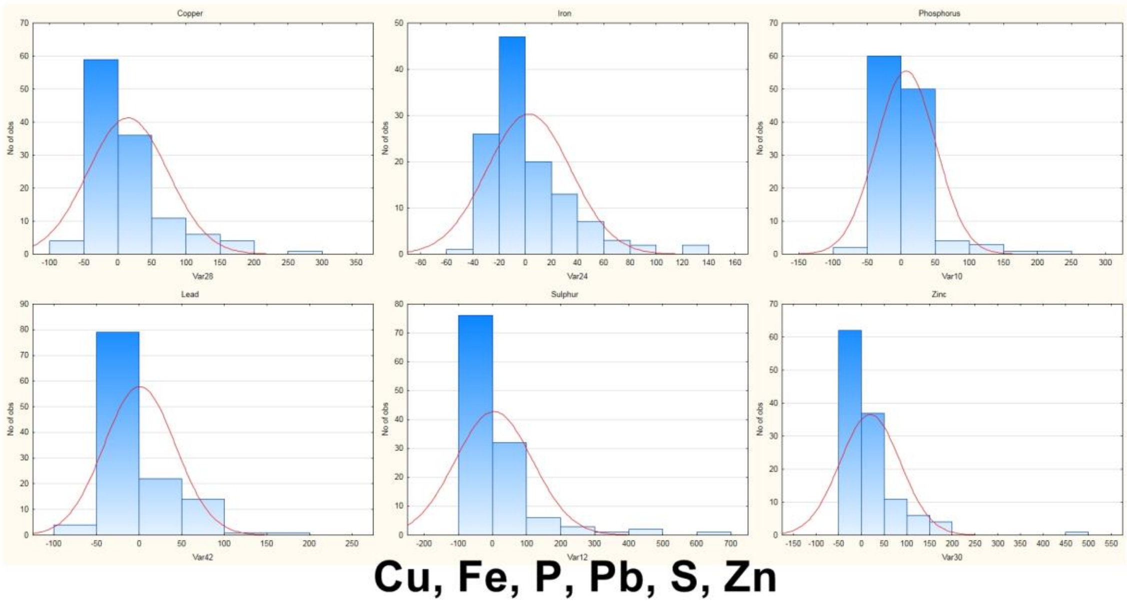


Fig. 24: Histograms of this last group carry a similar sign of a major negative deviation from the mean, which shows the weaker concentration of described chemical elements at the site. Nonetheless, all of these elements were sometimes detected in very high concentrations, but only in a limited number of samples (created by the author).

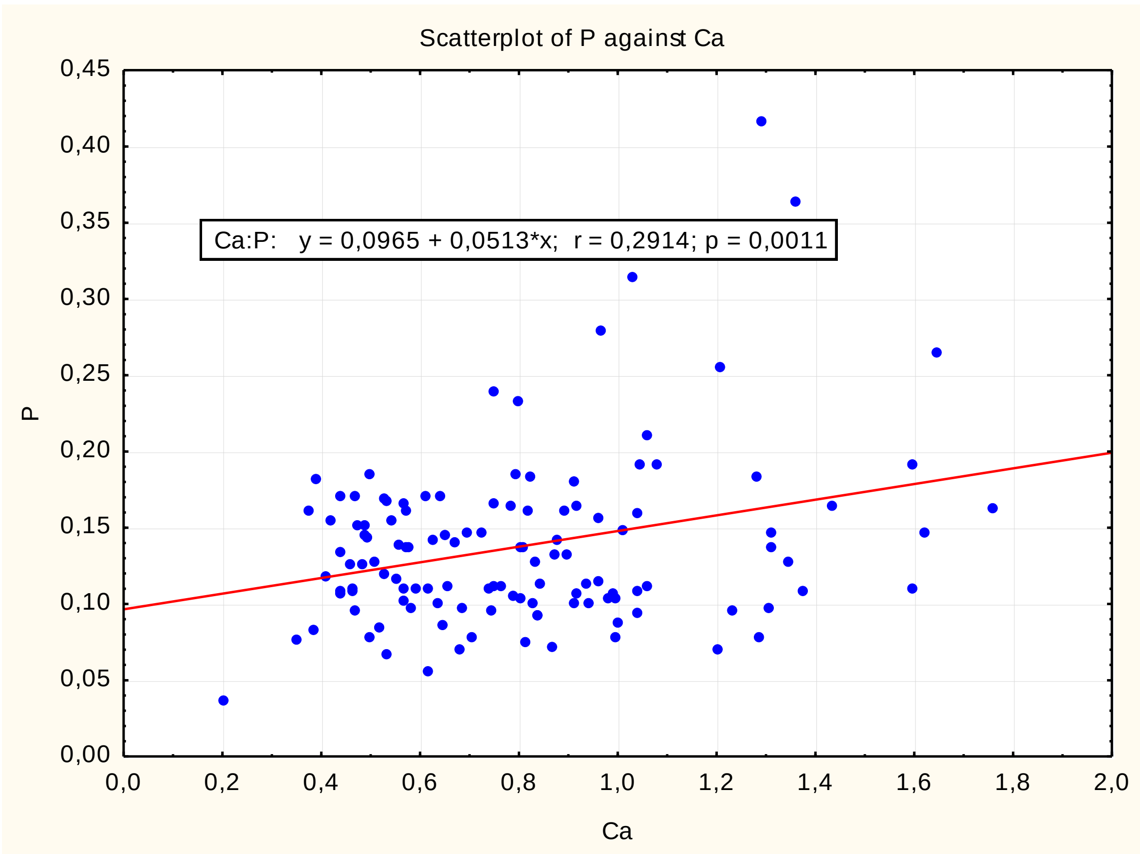


Fig. 25: Scatterplot of Ca and P, created in Statistica 12.5 (created by the author).

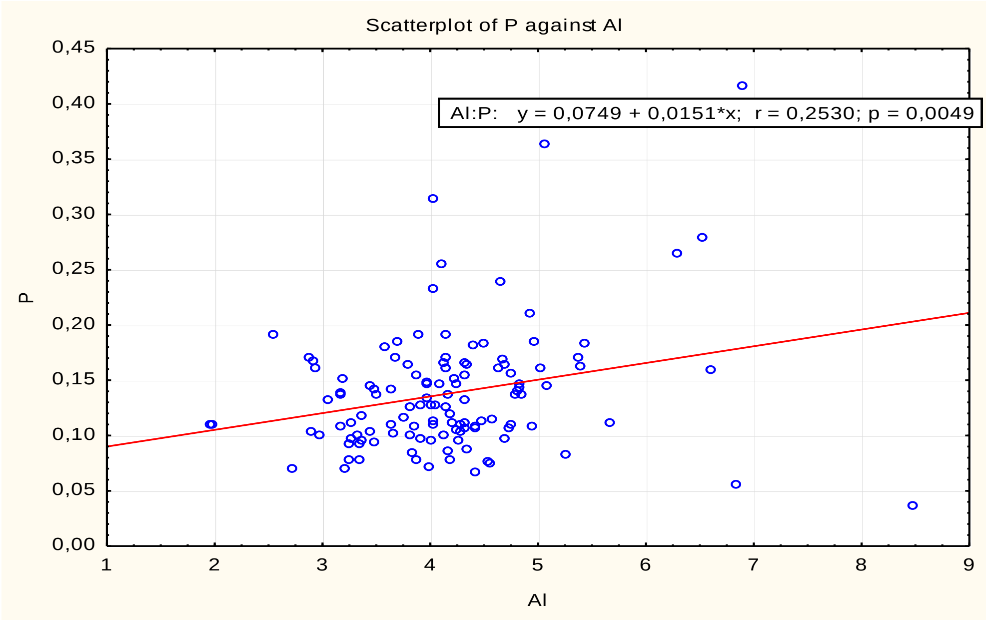


Fig. 26: Scatterplot of P and Al, pXRF data from 2015 (created by the author).

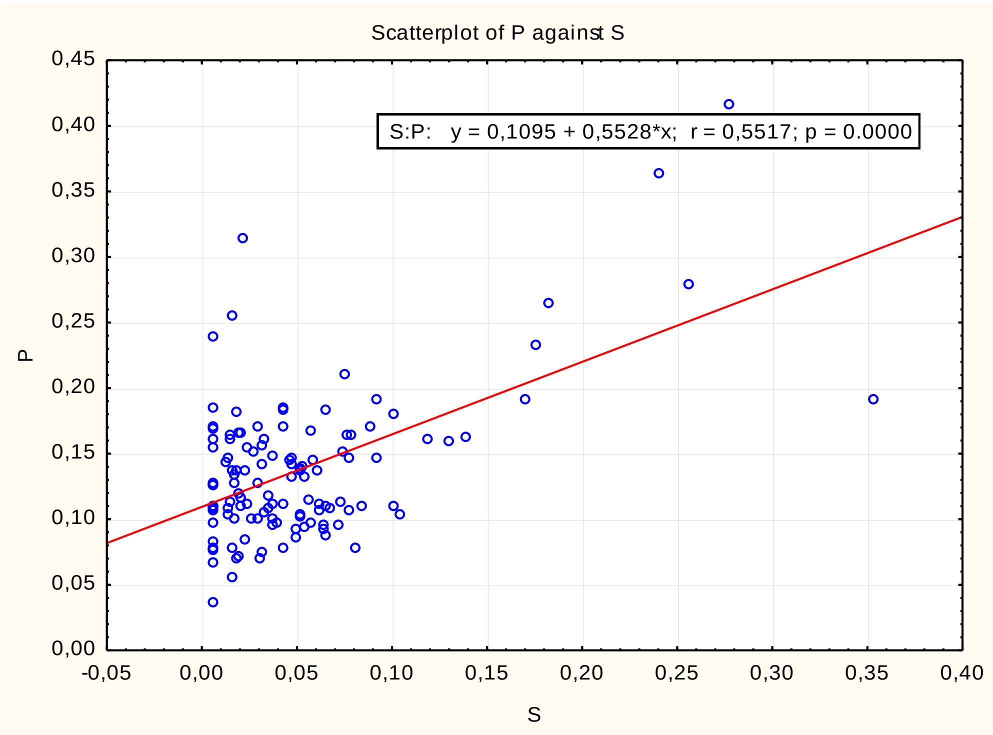


Fig. 27: Scatterplot of P and S (created by the author).

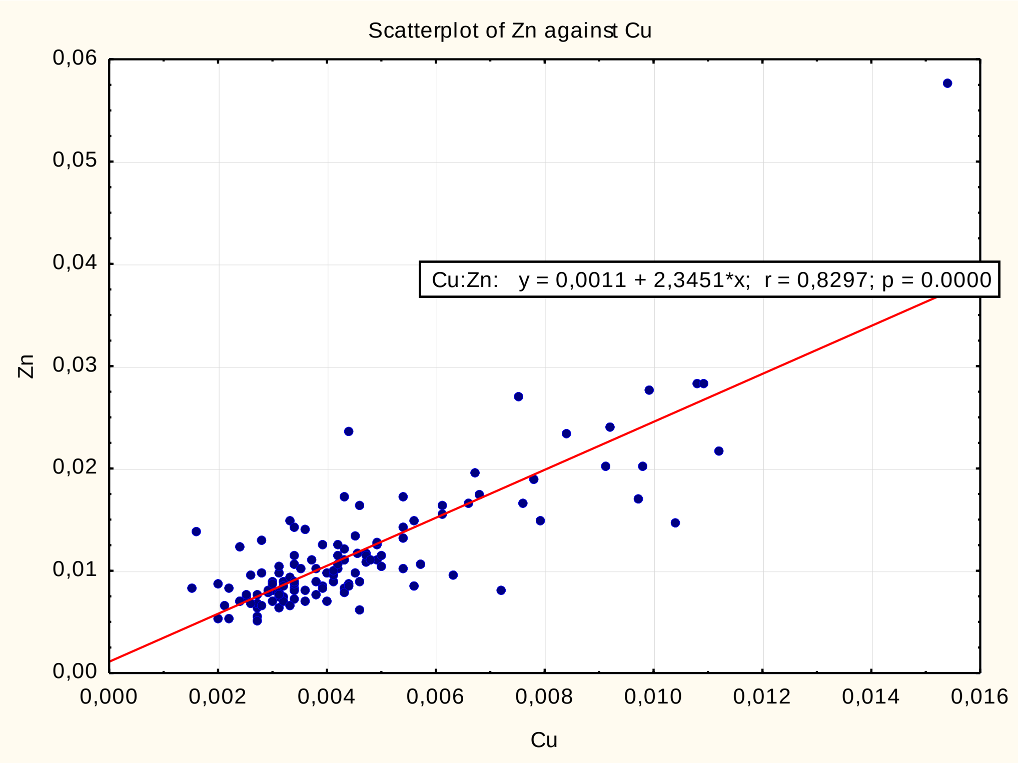


Fig. 28: Scatterplot of Zn and Cu, showing the strongest positive linear correlation found in the data from the site Plzeň-Hradiště (created by the author).

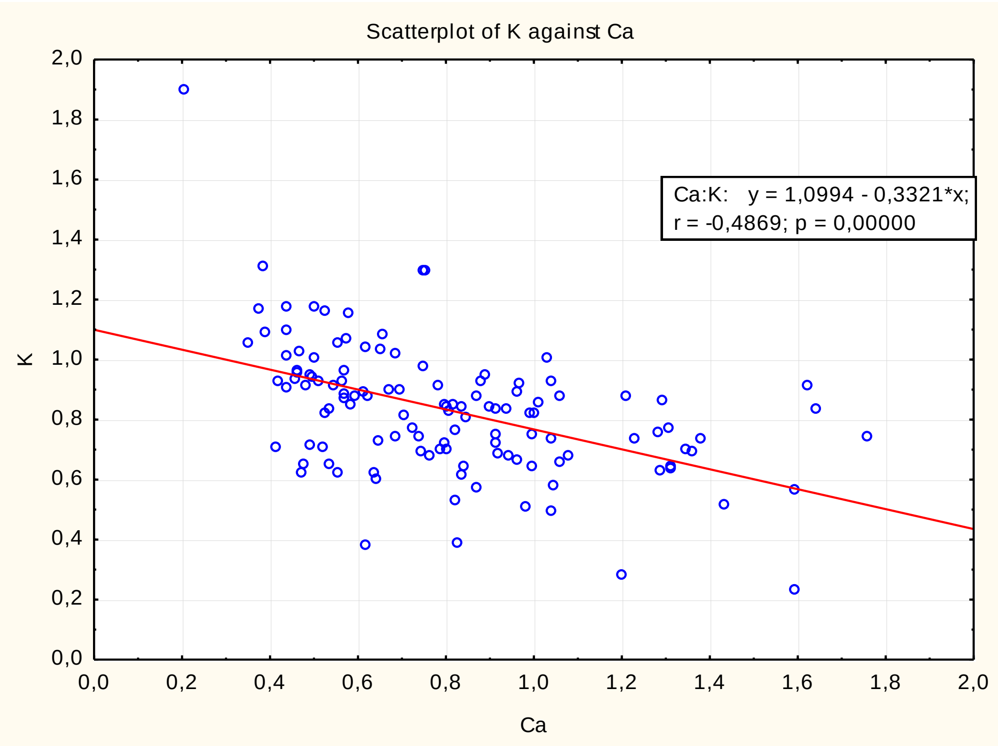


Fig. 29: Negative linear correlation of K and Ca (created by the author).

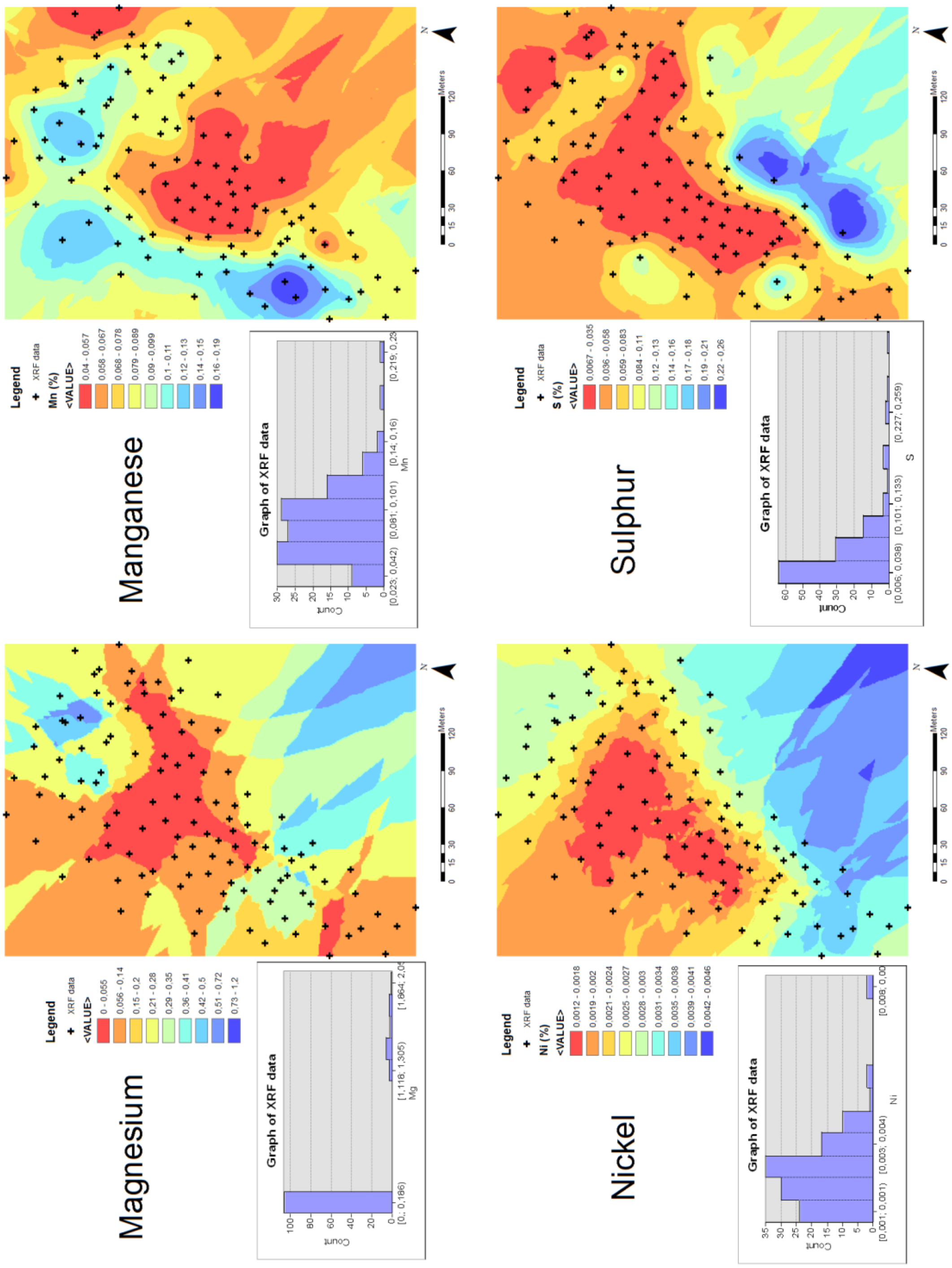


Fig. 30: Interpolated map created by the author.

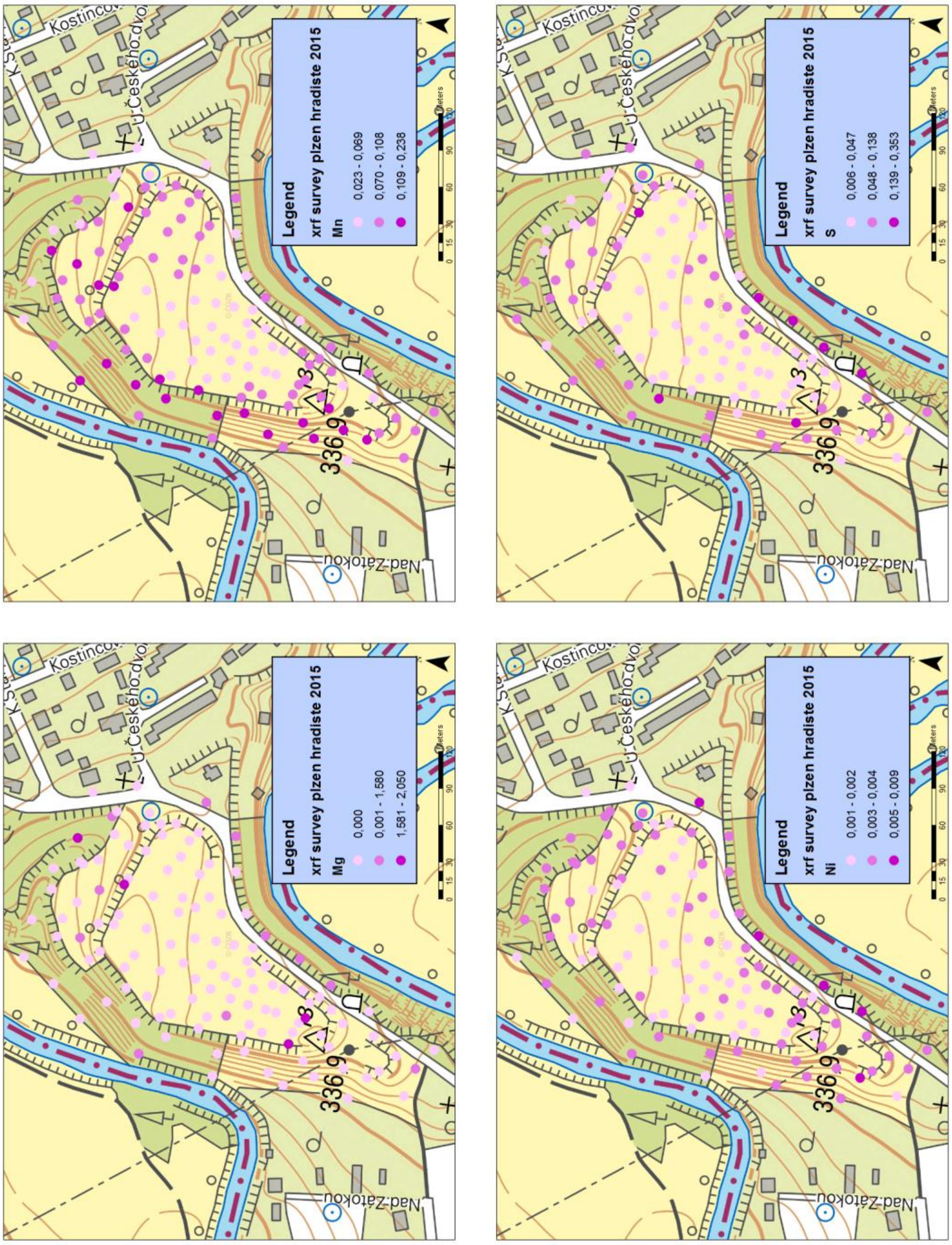


Fig. 31: Map of elemental distribution of Mg, Mn, Ni and S (created by the author).

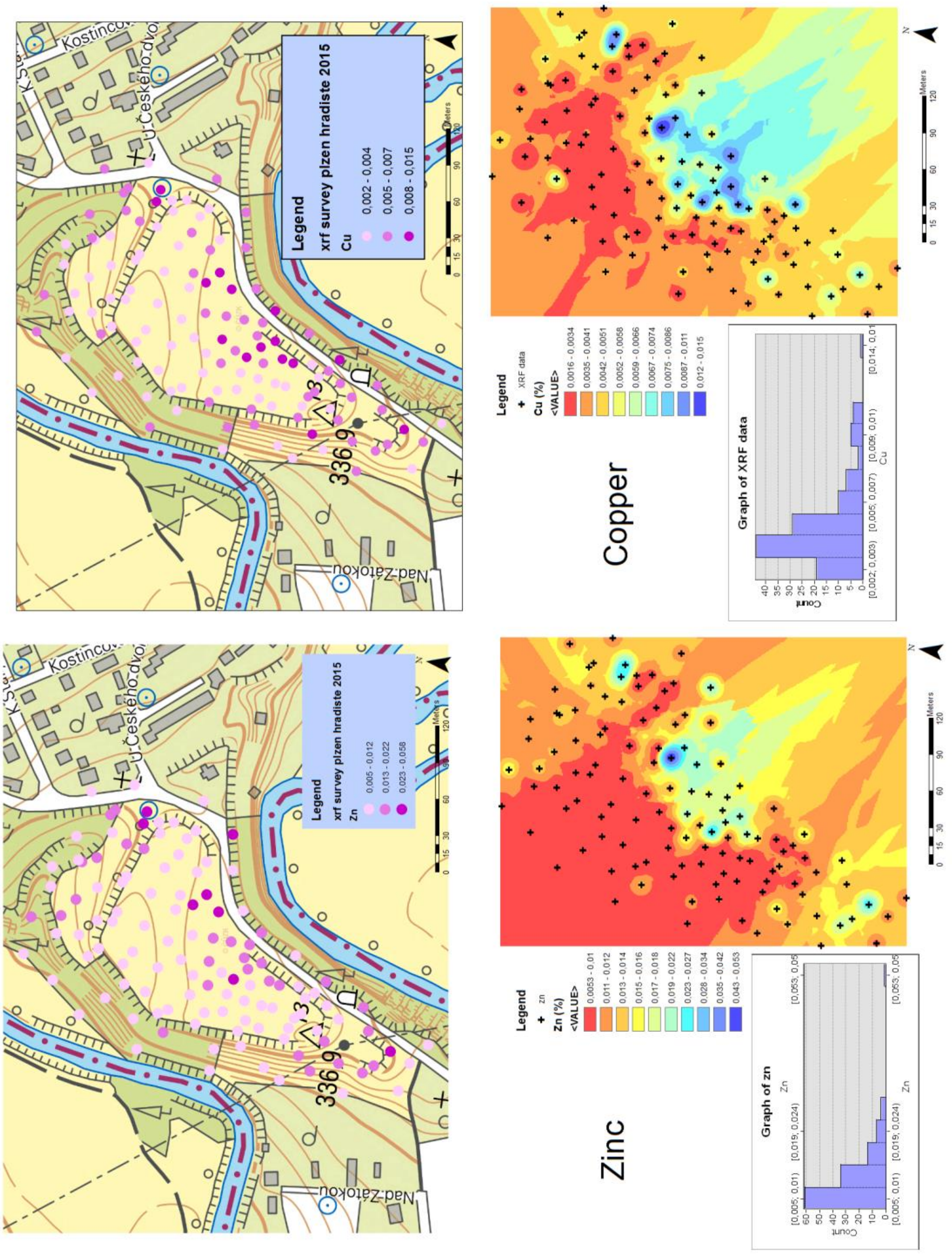
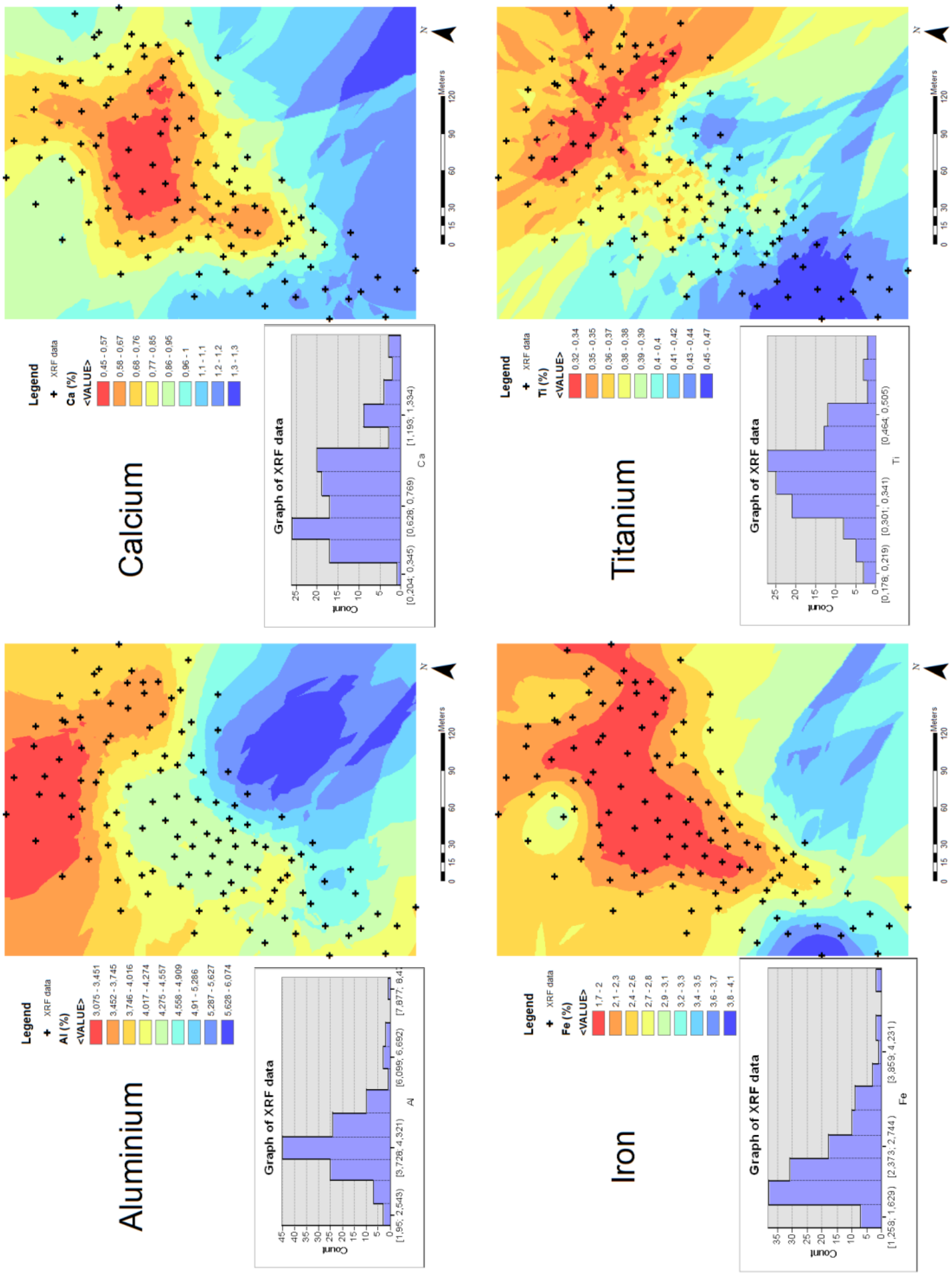


Fig. 32: Interpolated maps and maps of distribution of Zn and Cu (created by the author).

Fig. 33: Interpolated map created by the author.



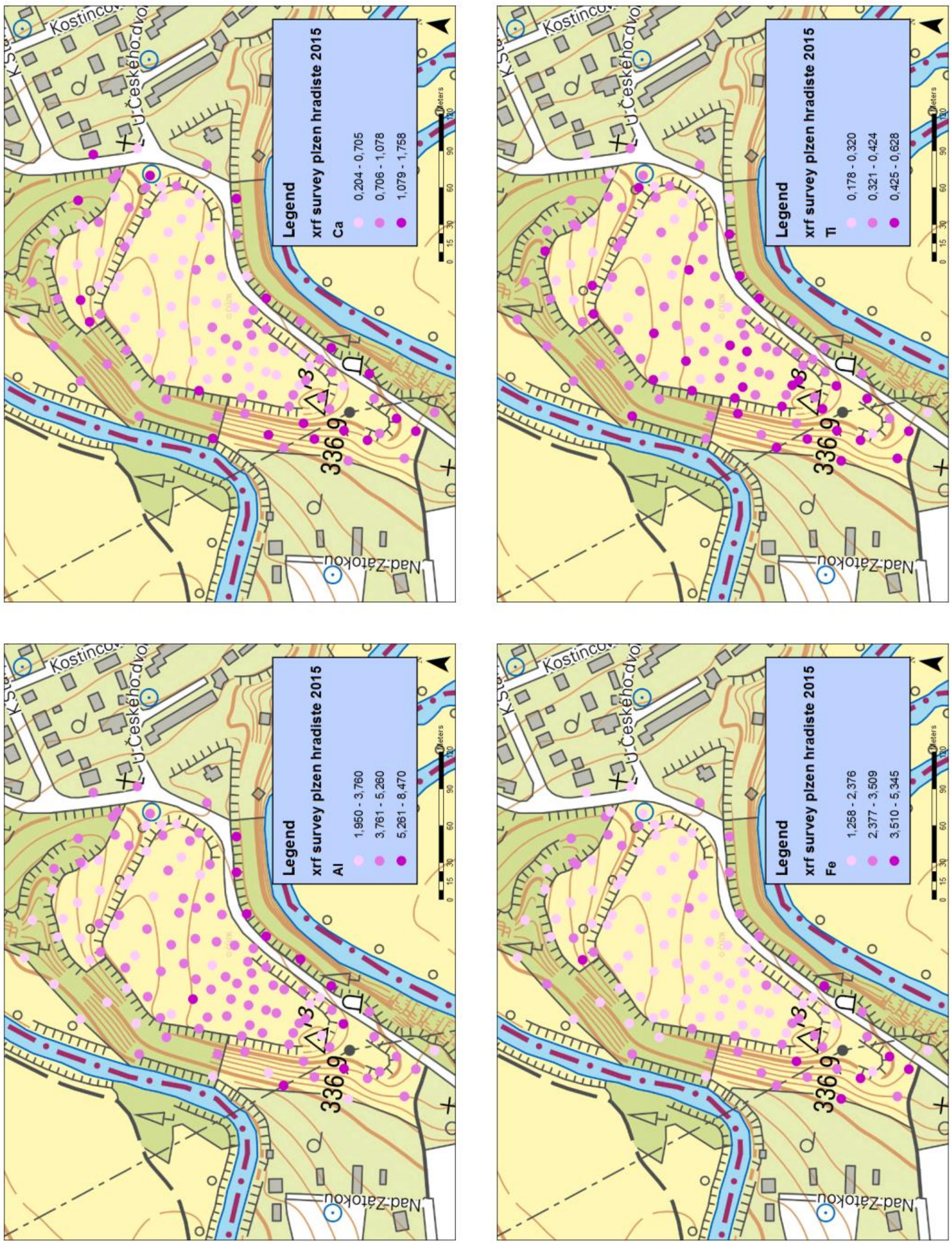


Fig. 34: Maps of elemental distribution (created by the author).

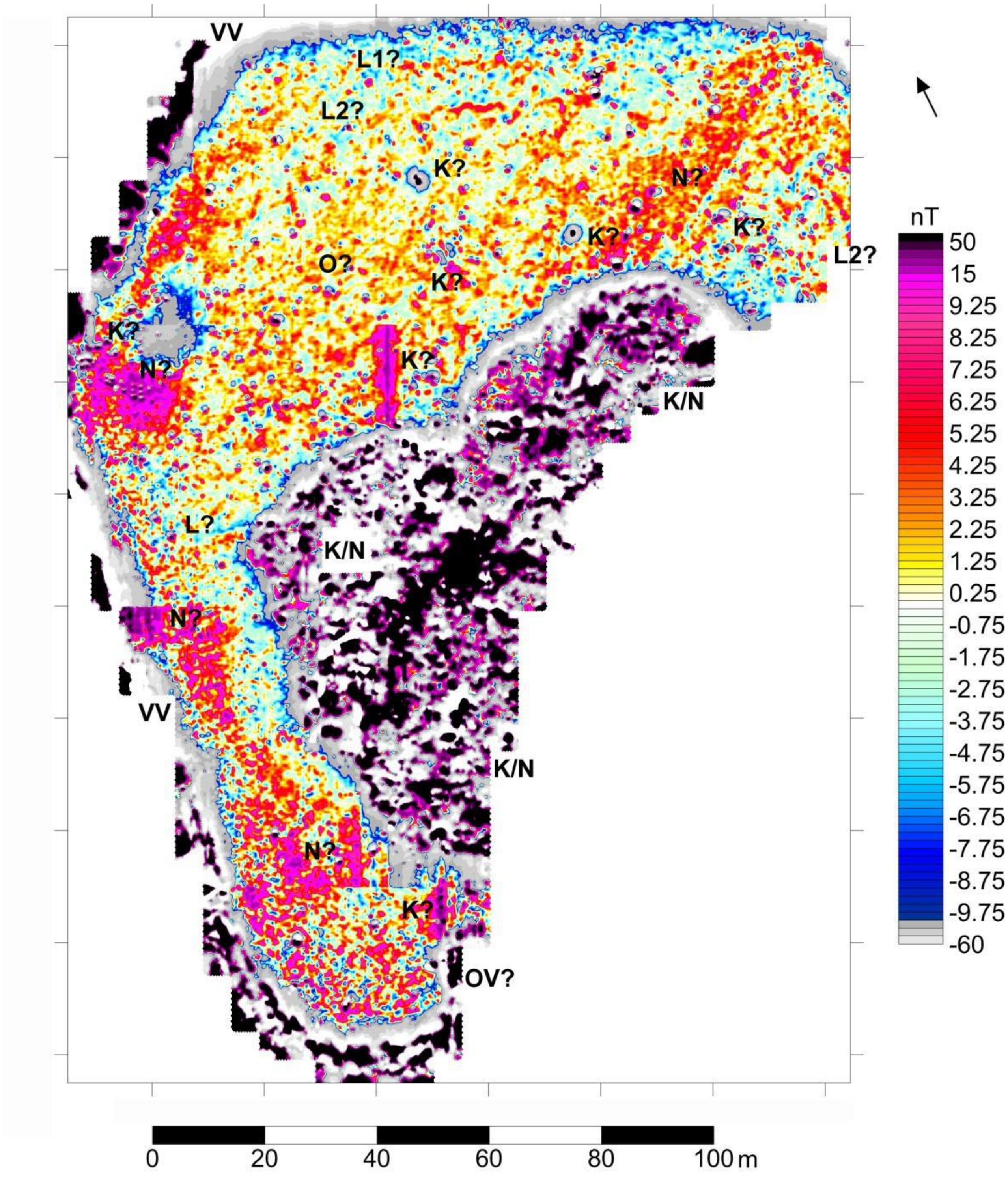


Fig. 35: The magnetometric survey detected on south-east of the site an arc-shaped curve of strongly magnetic line of the vitrified rampart heading back towards the inner area of a site. (R. Křivánek 2013, 8; unpublished report). (OV? stands here for possible curved ending of the rampart).

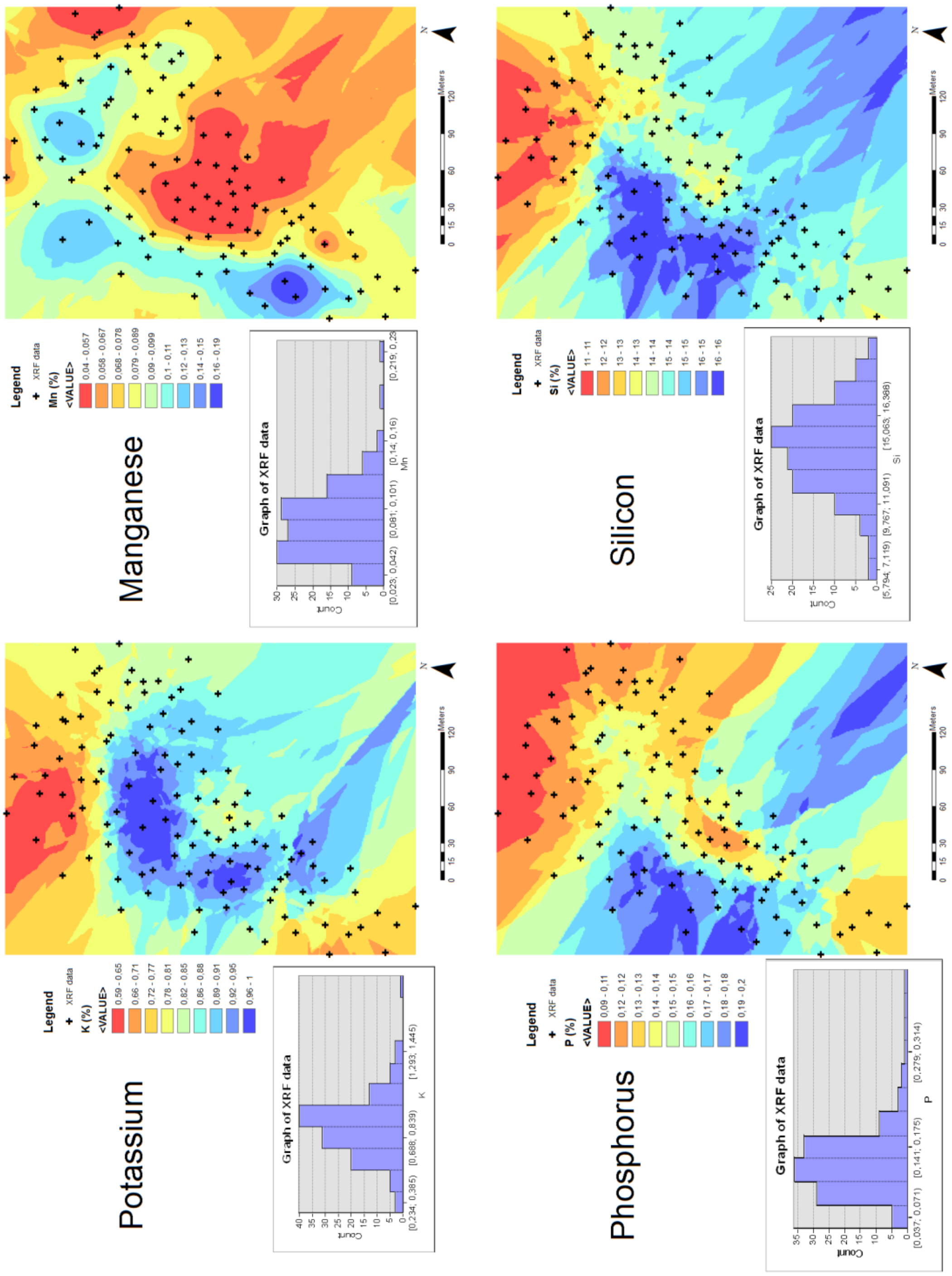


Fig. 36: The interpolated maps created by the author.

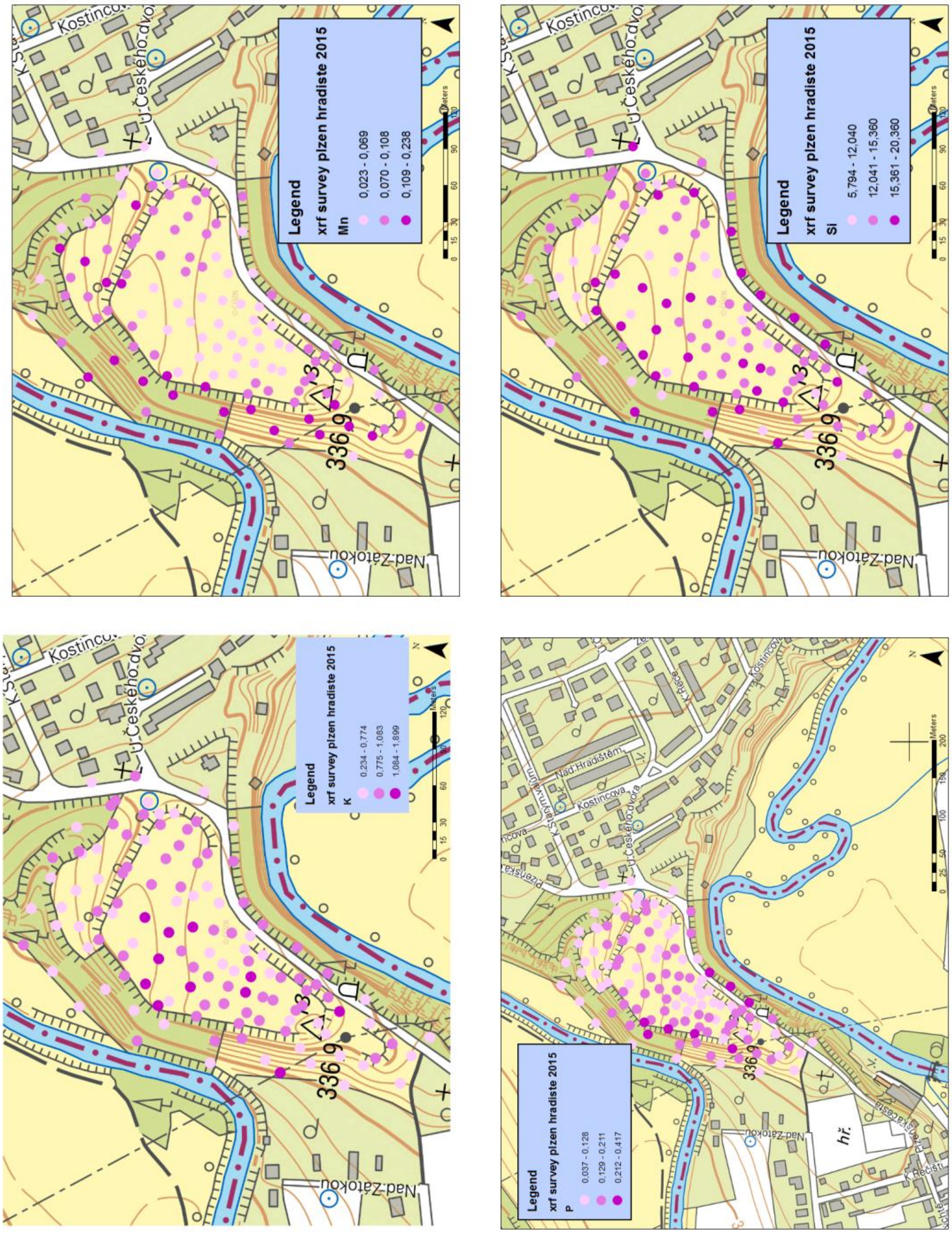


Fig. 37: Maps of elemental distribution created by the author.

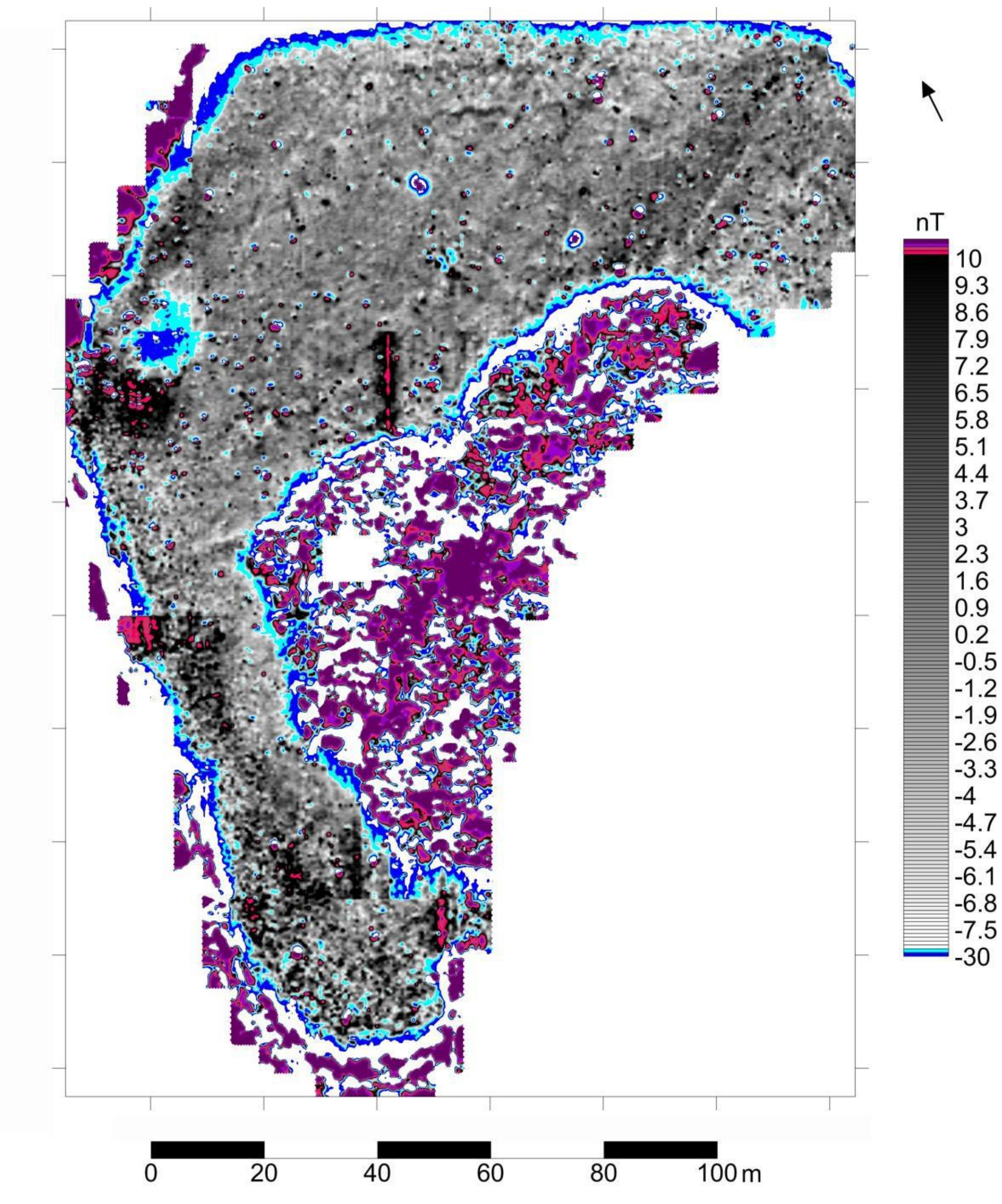


Fig. 38: Result of the magnetometric survey at the central part of the enclosed settlement, the then sand quarry and vitrified materials of the rampart are clearly visible (R. Křivánek 2013, 5; unpublished report).

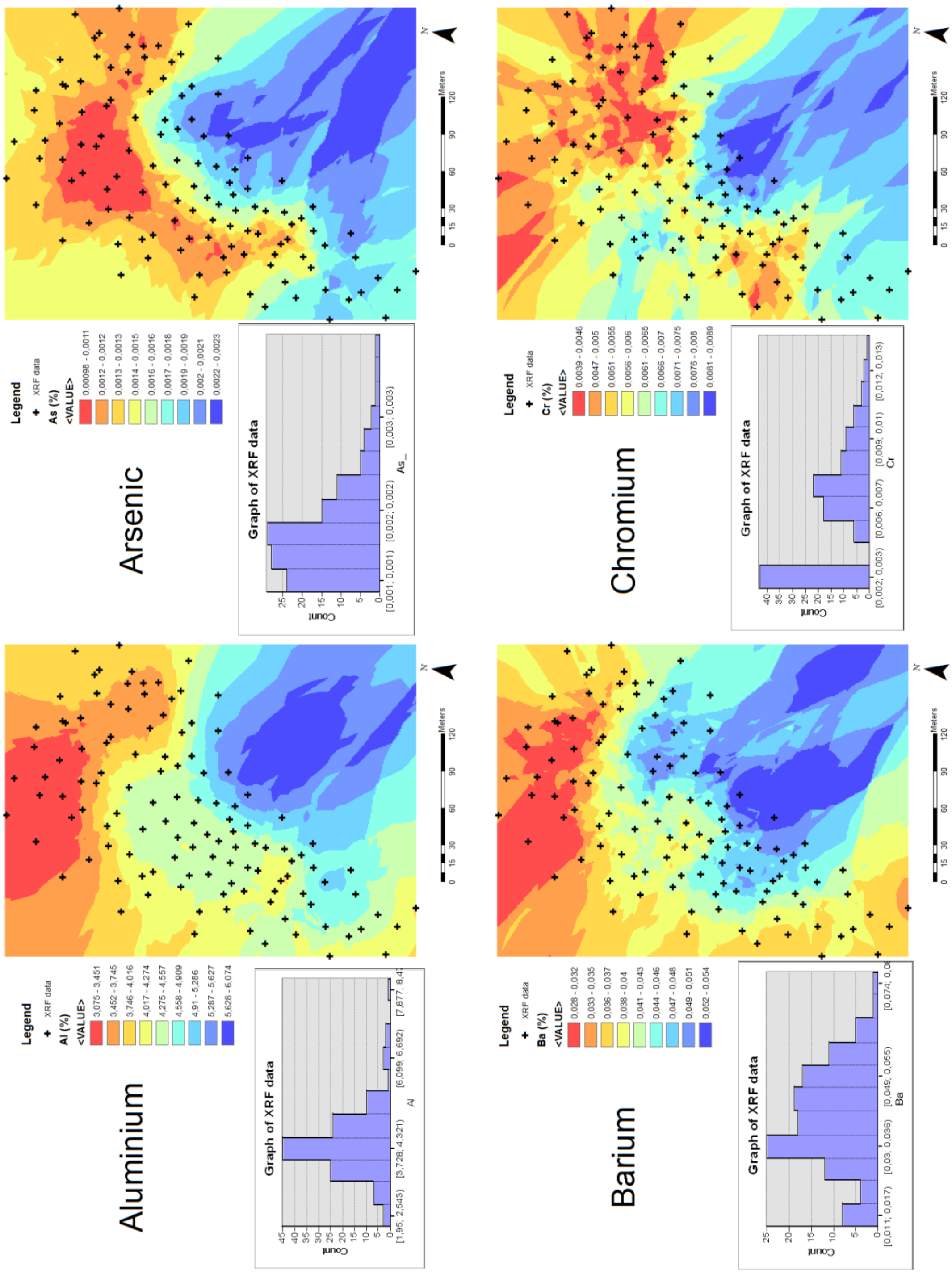


Fig. 39: Interpolated maps of elements created by the author.

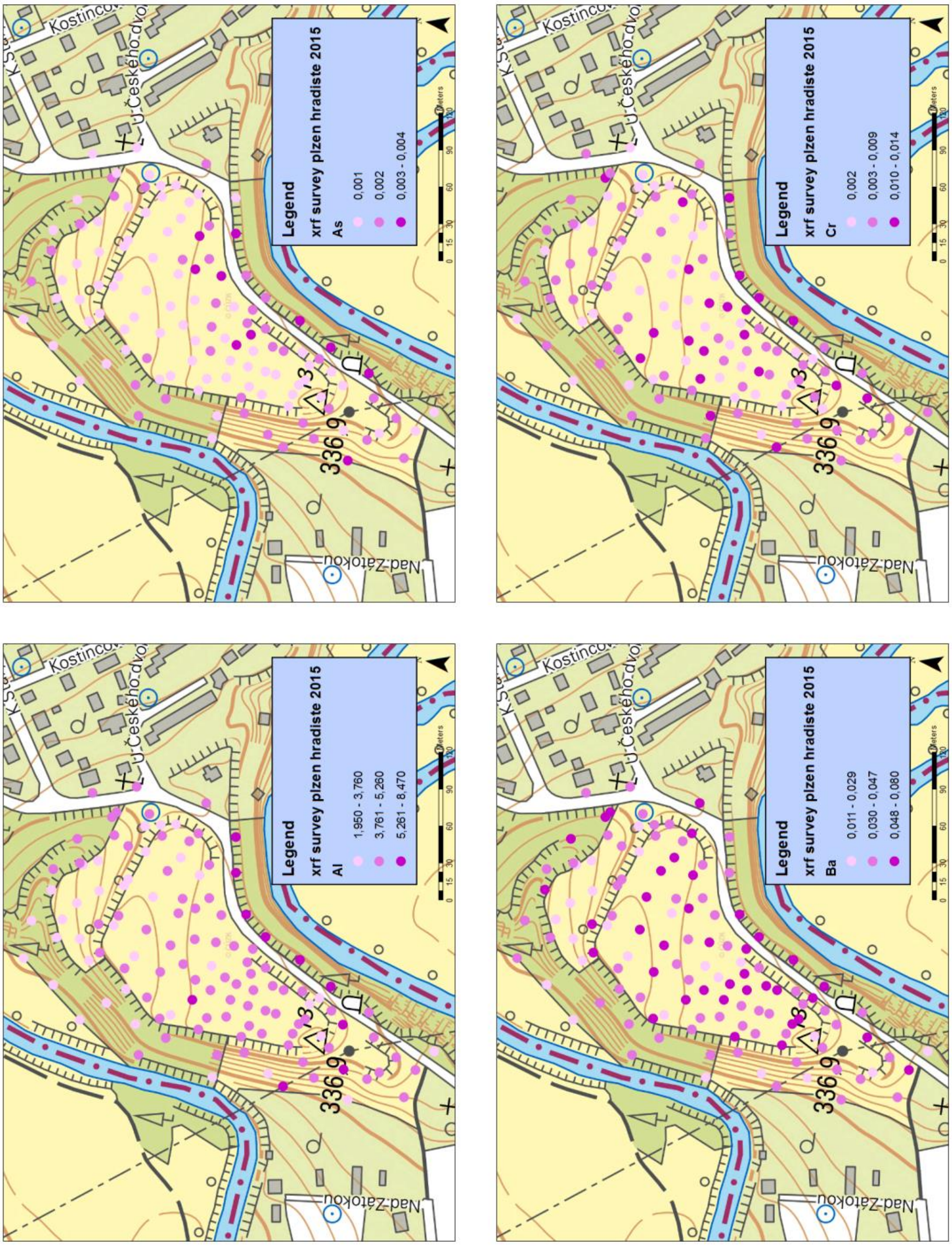


Fig. 40: Maps of elemental distribution created by the author.

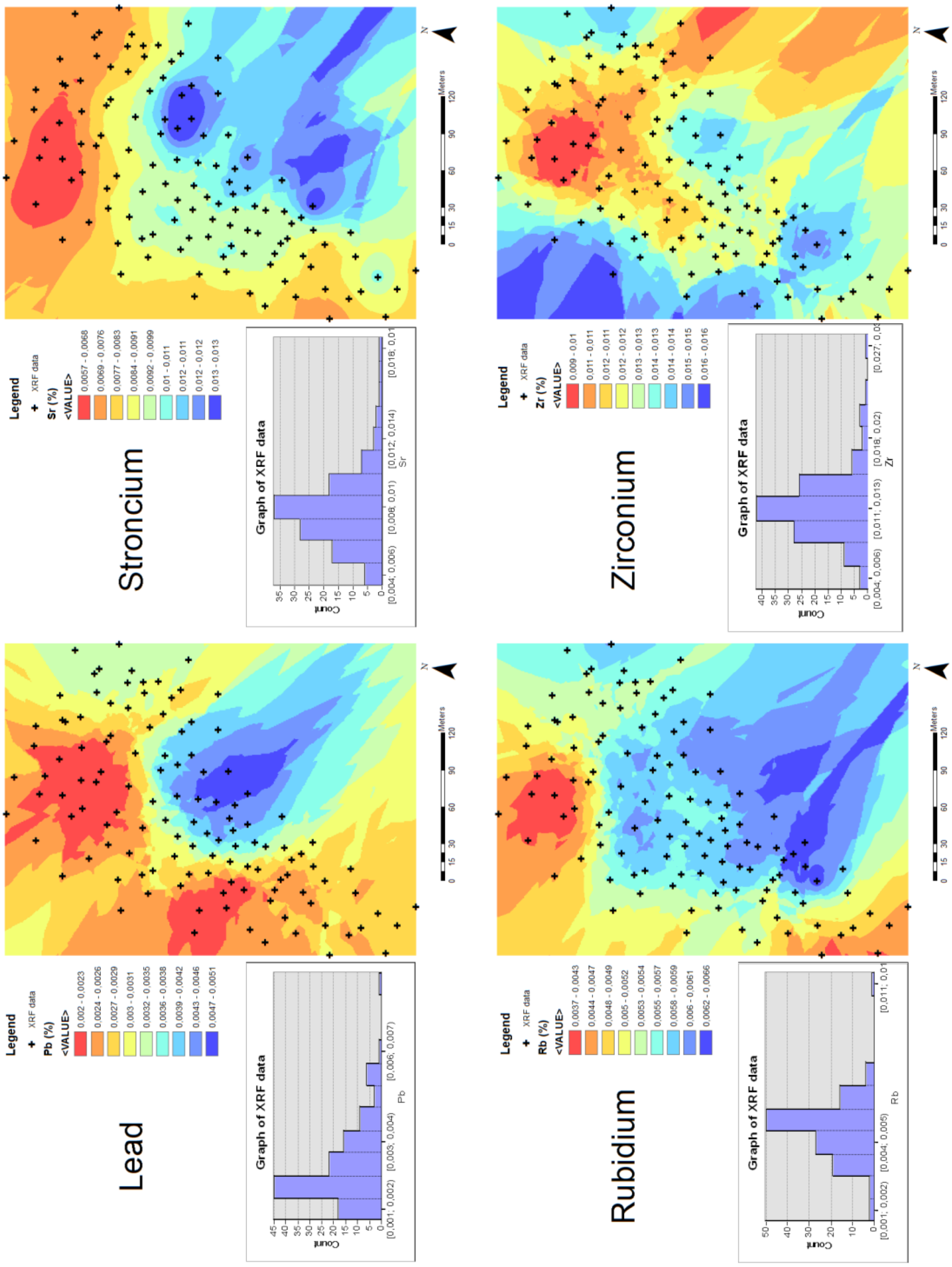


Fig. 41: Interpolated maps created by the author.

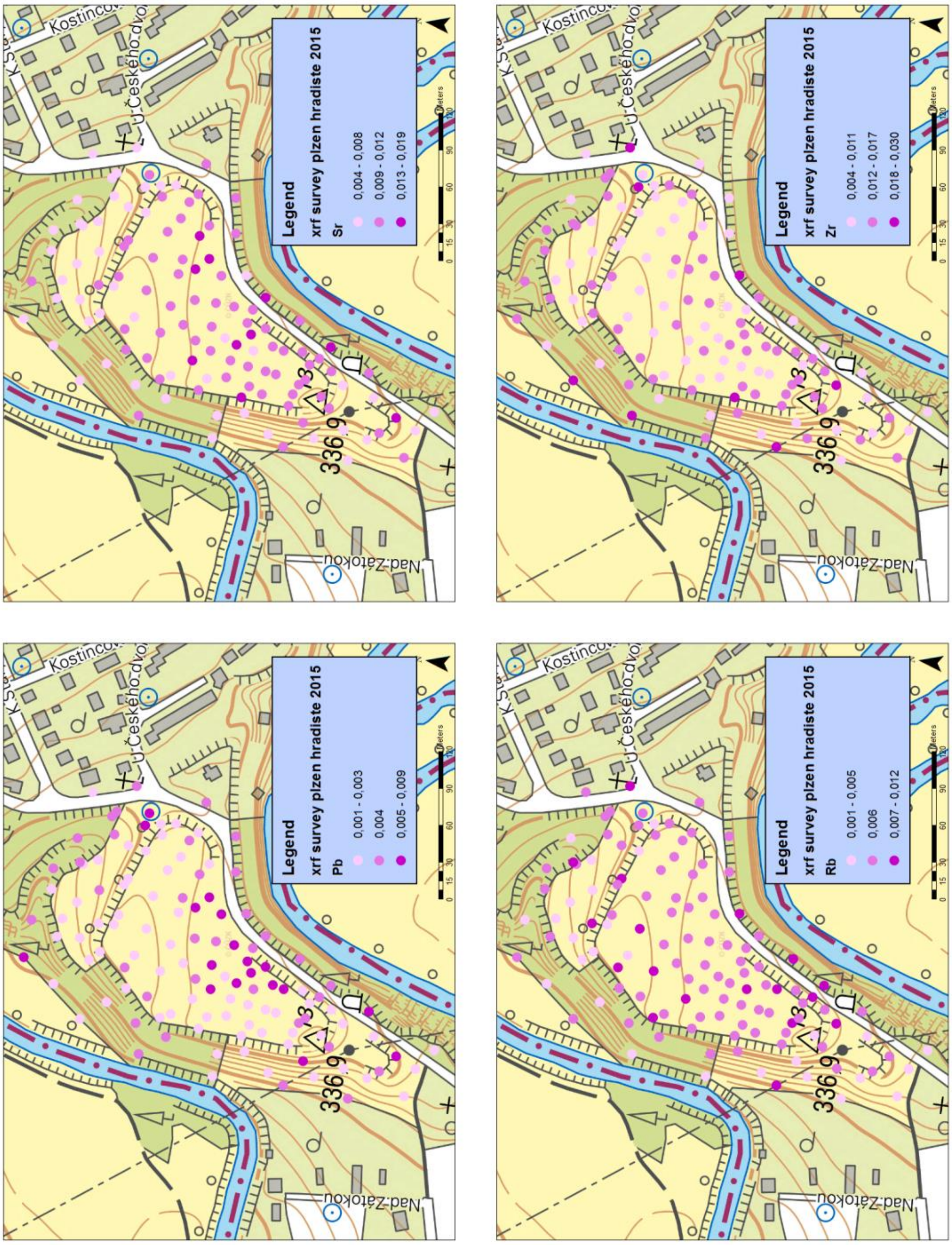


Fig. 42: Maps of elemental distribution created by the author.

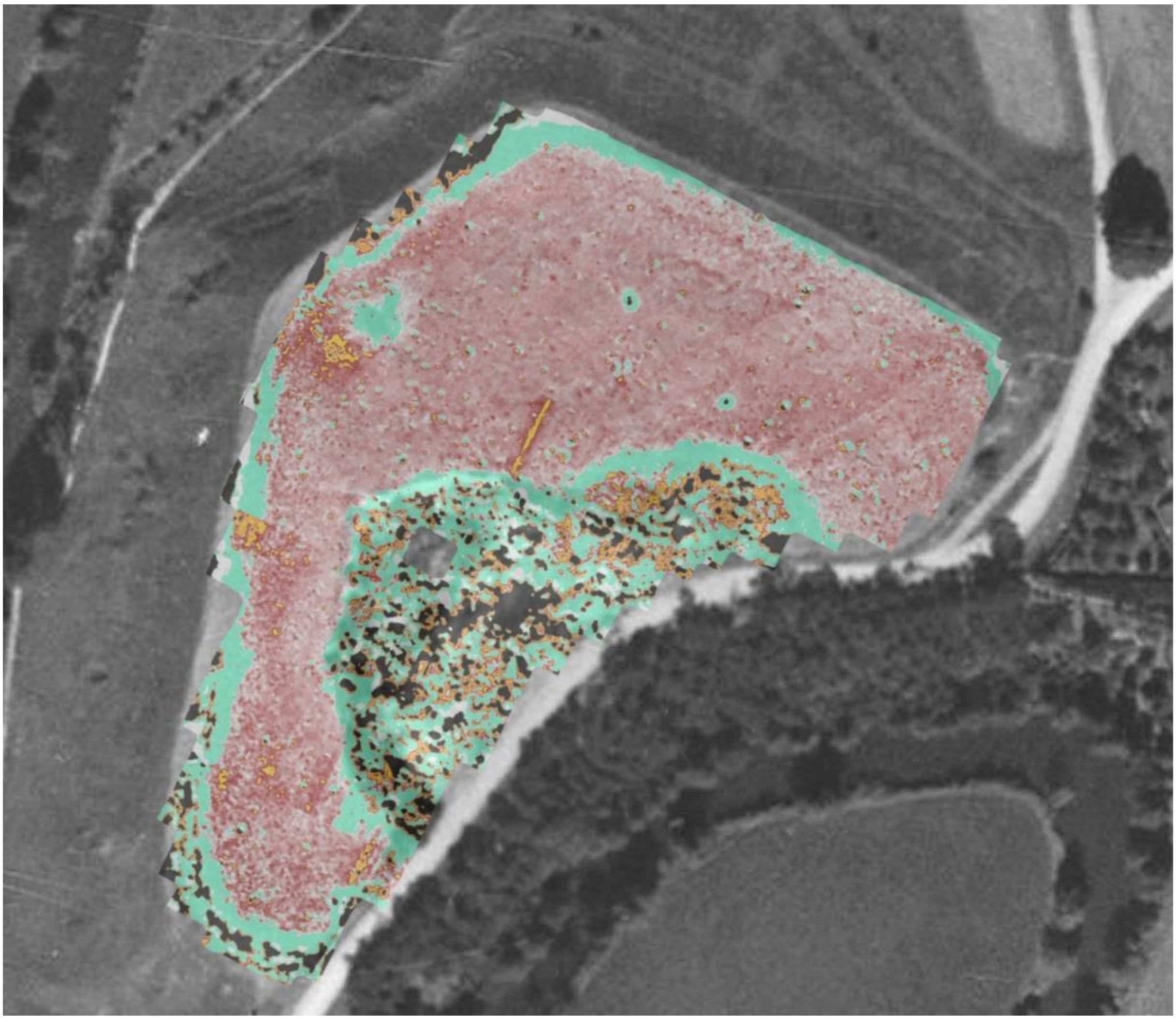


Fig. 43: A combination of an aerial picture from 1956 and output of the magnetometric survey performed by R. Křivánek (R. Křivánek 2013, 16; unpublished report).